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TENSION, COMPRESSION AND FATIGUE PROPERTIES OF SEVERAL

STEELS FOR AIRCRAFT BEARING APPLICATIONS

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# INTRODUCTION

Aircraft turbine bearings must operate under severe conditions of both load and temperature. An important problem is to increase both engine reliability and performance by increasing the bearing life of presently used alloys and by applying new alloys with greater strength at elevated temperature.

The common bearing steel is SAE 52100 heat treated in the range between 58 and 62 R<sub>c</sub>. A gradual improvement in SAE 52100 bearing life has been observed over the past 10 years. As pointed out by Cobb (1) this has probably resulted from improving the cleanliness of the steel. Thus, Barnes and Ryder (2) have shown that the minimum bearing life of SAE 52100 is greatly improved by vacuum melting. Similar beneficial effects of vacuum melting have been reported by Frith (3) and Styri (4) on the rotating beam fatigue strength of this alloy, and by Ransom (5) on the fatigue strength of SAE 4340.

The need for satisfactory bearing performance at temperatures exceeding the useful range of SAE 52100 has lead to the consideration of vacuum melted tool steels (1), (3), (6), and (7). These steels exhibit strong secondary hardening characteristics and hardnesses of 60 R<sub>c</sub> and above may be obtained by tempering at temperatures somewhat over 1000° F.

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Very little information exists regarding the static mechanical properties or the fatigue characteristics of such steels. However, the properties in static bending have been reported by Grobe and Roberts (8) and by Hamaker, Strang and Roberts (9). Values of bend strength increase with increasing hardness to over 600,000 psi at hardnesses exceeding 60 R<sub>C</sub>.

The direct evaluation of effects of melting practice, heat treatment or alloy composition on bearing life are greatly complicated by the large number of tests necessary and complex nature of the equipment. The above discussed beneficial effect of vacuum melting on both laboratory fatigue properties and bearing life suggest that there may be at least a qualitative relation between the results of these two types of tests. Furthermore, it has been claimed by various investigators that the bending fatigue endurance limit for heat treated steels is directly proportional to the tensile strength. However, such a simple relation appears to be at best confined to low hardnesses and restricted to certain compositions (3), (10) and (11). More recently, it has been hypothesized by Cohen and his coworkers (12) and (13) on the basis of rather meager evidence that both the tensile elastic limit and the endurance limit of low alloy steels are similarly related to the hardness. It is suggested that the well known decrease in elastic limit at high hardness levels is associated with a corresponding decrease in endurance limit. It might therefore be possible to estimate the influence of a given metallurgical variable on the bearing life by examining its effect on the tensile elastic limit, or perhaps on some other static mechanical property. To critically examine such a possibility data is needed for the static, compressive and fatigue properties over a wide range of hardness.

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The object of the present investigation was to establish the influence of heat treated hardness level on the room temperature and 350° F static and fatigue properties of electric furnace melt and vacuum melt SAE 52100 and on the room temperature static properties of three tool steels. The static and fatigue properties of the tool steels were also investigated for one hardness level (62 R<sub>C</sub>) at both room temperature and 500° F. In addition, a few tests were made to investigate the influence of minor variations in heat treatment on the 500° F fatigue strength of the tool steels. An attempt was made to determine the magnitude of first and second order residual stresses for all alloys as a function of hardness level. The results are analyzed to permit comparison of the mechanical properties of the tool steels with those of SAE 52100 and to explore the possibility of a relation between static and fatigue characteristics.

#### MATERIAL

Three electric furnace heats and one induction vacuum melted heat of SAE 52100 were investigated. Two of the electric furnace heats (Nos. 2 and 3) were available only in small quantities and represent material for which bearing life data was determined in another investigation (see appendix II). Three induction vacuum melted tool steel compositions; Halmco, M-1 (AISI TMO) and (AISI M-50) were also included. The composition and source of all these materials is given in Table I. With the exception of SAE 52100, Heats 2 and 3, all alloys were received as 1/2 inch diameter rod. These latter two heats were furnished in 9/16 inch diameter.

The hardibility of the two principal heats of SAE 52100 is shown in figure 1 in comparison with typical data supplied by one steel company. The ASTM inclusion ratings for the various alloys are given in table II.

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The various heat treating schedules employed are given in Tables III and IV. These include a series of experimental treatments designed to yield a range of hardness from 50 to 65 R<sub>C</sub>. In addition, commercial heat treatments are included which yield a hardness of about 62 R<sub>C</sub> and are presumably representative of present day bearing practice.

#### PROCEDURE

The very high hardness level of the steels and the consequent limited plasticity required that special techniques be employed in the tension tests to minimize bending stresses caused by misalignment. Similar precautions were necessary in the compression test to obtain reliable values of the elastic properties and yield strengths. Specimens were rough machined from the bar stock to about 0.035 inch oversize, heat treated and then finish machined by grinding and polishing.

Tension and compression testing. - Tensile specimens with highly concentric ground threads, figure 2, were employed in conjunction with an axial loading fixture (14). This technique permitted reliable tensile strengths to be determined at the highest hardnesses. Compression tests were performed in a ball bearing die set using heavy parallel ground compression anvils with a special centering device. As a further aid in reducing bending stresses the edges of the accurately machined, square ended compression specimens were slightly rounded. Room temperature checks of the alignment were made using three wire resistance gages spaced 120° apart on longitudinal elements of the specimens. Typical examples of elastic stress-strain curves from these three gages are shown in figure 3 for a tension and compression specimen. Perfect alignment would be indicated by identical curves from the three gages. As can be seen, this ideal

condition is closely approached, the maximum bending stress being approximately 1 to 2 percent of the average tensile stress and 2 to 4 percent of the average compressive stress.

For elevated temperature testing fundamentally the same techniques were employed. In the case of compression tests the anvils were extended inside of a split furnace. For both tension and compression tests the temperature variation along the gage length was within  $\pm 2^{\circ}$  F.

Fatigue tests. - The specimens employed at room temperature were of standard design, figure 4, and finish polished in the longitudinal direction<sup>1</sup>. Standard R. R. Moore rotating bending fatigue machines were employed for testing these specimens.

For tests at elevated temperature the specimens, figure 4, were provided with a  $1\frac{3}{4}$  inch cylindrical length at each end. This design permitted the installation of a tubular-electric resistance furnace over the test section. In order to accommodate the furnace the fatigue machines were modified to increase the distance between the spindles by  $3\frac{1}{2}$  inches. A water cooled jacket was fixed between the face of each spindle housing and the furnace end. Temperature control was effected by means of a thermocouple inserted into a bore through one end of the specimen which terminated  $7/8$  inch from the minimum diameter. The temperature variation at the test section did not exceed  $\pm 10^{\circ}$  F.

Strain measurements. - The determination of elastic limit in tension and compression at room temperature was by a "load release" method which has been employed previously by other investigators. For this method an

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<sup>1</sup>Finish polishing was done in three steps using wet 80, 280, and 500 grit paper in this order.

SR-4, Advance wire strain gage was Duco cemented to the specimen and the load was increased in increments, unloading after each increment. The permanent set (plastic strain) after each unloading was recorded. Theoretically the elastic limit would be represented by the highest stress value not producing plastic strain. The curve resulting from a plot of the stress against permanent set should be vertical (zero plastic strain) up to the elastic limit and then exhibit a continuous deviation in the direction of increasing plastic strain. Curves of this nature have been reported by MacAdam (15) using highly sensitive mechanical strain gages. Unfortunately, the use of SR-4 gages introduces difficulties. These are manifest by the indication of "reverse" plastic strains. This peculiar behavior is illustrated in figures 4 and 5 for tensile and compression tests respectively. Similar behavior has previously been reported by Muir, Averbach and Cohen (12) for tensile tests on low alloy steels. These investigators attributed it to an effect characteristic of the metal itself. However, it may be explained by behaviors characteristic of the strain gage which are encountered at very high strains. Wire resistance strain gages are generally employed at stresses much below those at the elastic limit of very hard steels. Under normal conditions the elastic limit of the wire is not exceeded throughout the test. However, in these tests the elastic limit of the wire was undoubtedly exceeded. Thus, the 0.2 percent yield strength of Advance wire is reported (16) as 65,500 psi. This would correspond to 82,000 psi stress in a steel specimen. It has been shown (17) and (18) that zero drift is encountered when the elastic limit of the wire is exceeded. Since, this elastic limit is below 65,000 psi, the permanent set data reported here can be considered

reliable only at specimen stresses somewhat below 82,000 psi. The authors ascribe the observed reverse strains primarily to zero drift of the gage. This zero drift in combination with residual stresses could produce the peculiar variation in the amount of reverse strain with hardness and its different magnitude in tension and compression. Therefore, no real quantitative value of the elastic limit can be derived from the reported load release data. However, for purposes of comparison an "elastic limit" is defined as the highest stress resulting in an indicated zero plastic strain.

The 0.2 percent yield strength was determined on the same specimens used for the load release curves by extending the SR-4 readings slightly beyond 0.2 percent strain. This rather unconventional manner of determining yield strength was checked by use of an extensometer. Yield strengths determined by these two methods were essentially identical, as might be expected, considering the flatness of the flow curve in the yield region.

At elevated temperature strains in the tensile tests were determined by means of a Baldwin PS 5M microformer type extensometer attached to the specimen heads. The sensitivity of this instrument and its recorder was approximately 200 microinches per inch. In the elevated temperature compression tests the extensometer was arranged to sense the movement of the die set plattens. No attempts were made to determine elastic properties at elevated temperatures.

## RESULTS

The results obtained establish the influence of hardness (50 to 65  $R_c$ ) on the room temperature static tensile and compressive properties of several heats of SAE 52100 and three tool steels. In addition, the 350° F static properties of an electric furnace melt of SAE 52100 are presented as a function of hardness. Static properties at 500° F are shown for the three tool steels heat treated to 62  $R_c$  by a typical commercial heat treatment. In plots of the static properties the points shown are the average of at least two tests unless otherwise indicated. The spread between duplicate tests was in general less than  $\pm 5$  percent with a few elastic limit values differing by  $\pm 15$  percent.

Fatigue properties at room temperature are established as a function of hardness level (50 to 65  $R_c$ ) for several heats of SAE 52100 and for the three tool steels commercially heat treated to 62  $R_c$ . Fatigue data at 350° F is also presented for an electric furnace melt and an induction vacuum melt of SAE 52100 at several hardness levels. Fatigue properties at 500° F for the three tool steels are presented for one hardness level (62  $R_c$ ) obtained by a commercial and experimental heat treatment. Since the number of fatigue specimens available were quite limited, the majority of tests were confined to the lower stress levels, in order to best estimate the fatigue strength between  $5 \times 10^7$  and  $10^8$  cycles. The accuracy of the fatigue strength at  $10^8$  cycles is in no case better than  $\pm 10,000$  psi.

Static properties of SAE 52100. - The various heats of SAE 52100 possess only slight differences in their room temperature elastic limits and yield strengths, figures 8 and 9 in both tension and compression over the entire hardness range. Tensile strengths exhibited somewhat greater

differences particularly at hardnesses above 58  $R_C$ . Surprisingly the highest tensile strengths are observed for an electric furnace melt and not as might be expected for the vacuum melt.

The influence of hardness on all room temperature static strength properties except the compressive yield strength is similar, in that a nearly linear increase in strength is observed up to 58  $R_C$ , the strength values then continuously decrease with increasing hardness. In contrast, the compressive yield strength increases linearly to the highest hardness.

According to figure 9 the 350° F static properties of electric furnace melt SAE 52100 increase with hardness up to about 58  $R_C$  and then remain essentially constant.

It is noted at both room temperature and 350° F that the static properties in compression are distinctly higher than those in tension.

Static properties of the tool steels. - The room temperature static properties of the tool steels are shown in figures 10 and 11 as a function of the hardness. Some rather complex and unexpected trends are observed. While these are clearly indicated by the available data, additional tests would be necessary to establish them as general behavior for the alloys in question.

With the exception of the elastic limits the three tool steels differ little in their static properties except at the highest hardnesses. At hardnesses above about 62  $R_C$  the Halmo appears to possess the highest, and M-1 the lowest tensile ultimate and yield strength. The compressive yield strengths at high hardnesses are at essentially identical with the exception of the anomalous behavior of MV-1 at 62  $R_C$ . The elastic limits

in both tension and compression exhibit unexpected behaviors which render a comparison of the steels regarding this property difficult. Generally, it would appear that Halmo exhibits elastic limits higher than either M-1 or MV-1 at hardnesses less than about 60  $R_C$ . At higher hardnesses irregularities in the elastic limits are observed. However, Halmo appears to yield consistently high values.

The influence of hardness on the room temperature tensile yield and ultimate strengths appears reasonably well established. These strength values increase nearly linearly with hardness up to a maximum at about 62  $R_C$  with the exception of Halmo which exhibits a continuous linear increase to the highest hardness. The compressive yield strength shows a similar linear increase up to a hardness of about 62  $R_C$  for Halmo and M-1. For MV-1 an unexpected minimum was observed at 62  $R_C$ . Generally, the elastic limits in both tension and compression increased with hardness up to a hardness between 58 and 62  $R_C$  depending on the alloy. At higher hardnesses these values exhibit complex trends (particularly for MV-1) which may or may not be real. As might be expected a decrease in elastic limit is observed with further increasing hardness for tension tests. For compression tests a similar indication of a maximum is observed for Halmo and MV-1 while the elastic limit for MV-1 passes through a minimum.

The 500° F tension yield and ultimate strength and the compressive yield strength is given in table V. It will be noted that there is little difference between the three tool steels at a hardness of 62  $R_C$  regarding these static properties.

As was observed for SAE 52100 the room temperature and elevated temperature static properties of the tool steels in compression exceed those in tension.

Fatigue properties of SAE 52100. - Room temperature S-N curves at various hardnesses are given in figures 12 and 13. It will be noted that distinct endurance limits are not established. The results for the several heats may be compared in figure 14 which shows the fatigue strength at  $10^8$  cycles plotted against the hardness. It will be noted that the induction vacuum melt appears to be superior to the electric furnace melts. The influence of hardness on either the electric furnace or vacuum melted alloy is rather small, the fatigue strength being essentially constant from 54 to 65  $R_C$ .

At 350° F only a limited number of tests were made, figure 15, and the induction vacuum melt was evaluated only at 62  $R_C$ . The influence of hardness at 350° F can be estimated by comparing the 350° F fatigue strength at  $10^8$  cycles with that obtained at room temperature. Thus according to figure 16 the 350° F fatigue strength remains essentially constant up to about 56  $R_C$  and then decreases slightly to a lower constant value at hardnesses above about 60  $R_C$ . Again the results indicate the superiority of the vacuum melted alloy.

Fatigue properties of tool steels. - The room temperature and 500° F S-N curves are shown in figures 17 and 18 for the three tool steels heat treated to 62  $R_C$ . Because of the limited number of tests and excessive scatter fatigue strengths at  $10^8$  cycles are not well established. At room temperature the highest fatigue strengths ( $10^7$  -  $10^8$  cycles) are obtained for Halmo and the lowest for MV-1. At elevated temperatures the data is insufficient to establish clear differences between the steels or between the commercial and experimental heat treatment. The most consistent results both in regard to scatter and agreement between the two

heat treatments was obtained with Halmo and M-1 which both appear to possess nearly equal fatigue strengths. For MV-1 the 500° F fatigue strength appears to be highest for the commercial heat treatment which yields strength values about equal to the other two steels.

#### DISCUSSION OF RESULTS

In the following section the various observed mechanical properties will be further discussed in light of the residual stress measurements given in appendix I and compared with previously published information. Further, the possibility of a relation between static and fatigue properties will be explored.

Influence of residual stresses. - Maxima in the tensile and compressive elastic limits and in the tensile yield strength when plotted against the hardness have been observed in many investigations (11) of low alloy heat treated steels. Similar behavior has also been reported for the bend yield strength of tool steels (8) and (9) tempered to very high hardness. In addition it has previously reported (11) and (19) that the compressive yield strength is higher than the tensile yield and that this difference increases with the hardness. The magnitude of these effects appears to depend on the heat treating practice which sets the residual pattern.

Residual stresses in the investigated steels are reported in appendix I (see figs. I-1 and I-2). This data indicates tension strains in the (211) planes parallel to the surface as well as high microstrains both of which increase with hardness. Such results are not unexpected and may explain in part the shape of the trend curves when the static properties are plotted against the hardness, as well as the difference in strengths observed between tension and compression. The microstrains cause early

deviation of the stress strain curve from linearity and tend to depress the elastic limit and yield strength. The first order residual stresses arise primarily from compressive plastic surface deformations occurring during the quenching cycle. It may be assumed that on subsequent testing these surface fibers are subject to a type of "Bauschinger Effect." In tensile tests both the microstrains and this Bauschinger Effect combine to depress the flow curve at small plastic strains. These effects are reduced by tempering and consequently are most pronounced at the highest hardnesses (lowest tempering temperatures).

Thus, the static tensile yield and elastic limits pass through a maximum at some high hardness level. A maximum in the tensile ultimate is observed at approximately the same hardness since the fracture ductilities are so low (less than 2 percent) that neither the Bauschinger Effect nor the microstrains are completely eliminated by plastic flow. In compression the Bauschinger Effect is absent and consequently the elastic limits and yield strengths are higher than in tension and the maxima are absent.

Regarding the fatigue strength it might be expected to increase continuously with hardness in the absence of other effects. However, as seen from figure 14, it remains essentially constant above 52  $R_c$ . The same phenomena discussed above may be associated with this behavior. The fatigue test is, however, much more complex than the static tests and it is not possible to make meaningful conclusions from the limited data available. The literature (20), (21), and (22) only serves to emphasize the complexity of the problem when residual stresses are introduced primarily by heat treatment or machining.

Comparison of fatigue strengths for SAE 52100. - The present result that the fatigue strength of SAE 52100 does not decrease at high hardnesses is supported by less extensive data from several previous investigations (3), (4), and (23). This behavior is in contrast to the results of Garwood, Zurburg, and Erickson (24) who report the endurance limit for a number of low alloy steels passes through a maximum at high hardness levels. Apparently no generalizations can be made regarding the dependence of fatigue strength on the hardness at high hardness levels.

Values of rotating beam room temperature fatigue strength at  $10^8$  cycles for air melted SAE 52100 have been reported previously (3), (4), and (23). At bearing hardness levels these vary considerably. For example, Styri (4) reports about 120,000 psi for this alloy quenched and tempered to 63.5  $R_c$ , while Frith (3) gives a value as low as 80,000 psi. Generally, the results from those investigations (3) and (4) where a considerable amount of data is available at  $10^8$  cycles appear to indicate that no definite endurance limit exists for SAE 52100 heat treated to high hardness levels.

These large variations in fatigue strength cannot be simply explained. Fatigue properties depend in a complex manner on a number of factors including the residual stresses resulting from quenching and/or machining; the steel making practice and minor variations in the chemistry. As previously discussed, the effects of residual stresses are as yet obscure. Regarding the steel making practice it has been reasonably well established in this and in other investigations (3) and (4) that vacuum melting increases the fatigue strength. According to Frith (3) the fatigue strength of open hearth heats is higher than electric furnace melts. The

explanation for these differences produced by variations in the steel making practice may lie in the resulting inclusion and/or residual element content. Vacuum melting is known to reduce both residuals and inclusions. Thus, the vacuum melted SAE 52100 has a lower residual element content (table I) and a lower inclusion count (table II) than the air melted heats. Furthermore, it is noted that there are only small differences in the inclusion counts of the three air melted heats but that the room temperature fatigue strength of these three heats increases with a decrease of residual elements. These observations regarding the inclusion constant are difficult to account for on a quantitative basis. Thus, microexamination of fractures in this investigation failed to reveal any significant difference in their inclusion patterns. This observation is in accord with the results of Hyler, Tarasov, and Favor (25)<sup>1</sup> who report no positive correlation between fatigue strength and the size or location of inclusions in an SAE 52100 type steel. In contrast, Stulen, Cummings, and Schulte (26)<sup>1</sup> report the fatigue strength is strongly dependent on the size and location of inclusions.

Of interest in this connection is the work of Butler, Bear, and Carter (28) and Bear and Butler (29). It is shown that the failure of balls in simulated service tests occurs preferentially at the location of inclusions. Furthermore, when the rolling direction was so controlled that the maximum stress was perpendicular to the fiber the ball fatigue life was considerably

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<sup>1</sup>These investigators examined fractured specimens. Negative conclusions were reached by Starkey, Marco, and Gatts (27) for SAE 4330, 4340, and 4350 on the basis of a statistical analysis of fatigue data and the SAE inclusions count on unfractured specimens.

reduced. These observations point to the importance of inclusions in ball bearing applications.

Effects of elevated temperatures. - A comparison of the static properties of electric furnace SAE 52100 as a function of the hardness is shown in figure 19 for room temperature and 350° F tests. The effect of increasing the test temperature conforms to the previously established behavior of low alloy steels (11). Thus, up to a hardness of about 58 R<sub>C</sub> the tensile strength is little reduced by the increase in test temperature, while the yield strength in tension or compression at 350° F is 10 to 15 percent lower than at room temperature. At hardnesses up to about 58 R<sub>C</sub> the steel is quite stable. However, at 62 R<sub>C</sub> and above the 350° F test temperature is close to or exceeds the tempering temperature and the structure is unstable. This instability permits a reduction in both microstrains and the previously hypothesized Bauschinger Effect. The result is a slightly higher tensile yield and ultimate at 350° F compared with room temperature and an increase in the spread between the compressive yield strengths at these two temperatures.

Raising the test temperature from room to 350° F results in approximately 15 percent loss in SAE 52100 fatigue strength up to 54 R<sub>C</sub> (see fig. 16). At higher hardnesses the test temperature approaches or exceeds the tempering temperature and specimens soften during the test. As might be expected the 350° F fatigue strength then decreases to a nearly constant value at hardnesses above 58 R<sub>C</sub>. In this range it is about 25 percent lower than the room temperature fatigue strength.

The 500° F properties of the tool steels in comparison with those at room temperature are given in table V for a hardness of 62 R<sub>C</sub>. At 500° F the tool steels should be quite stable and the effect of test temperature

would be expected to parallel that described above for SAE 52100 tempered to hardnesses less than 58  $R_c$ . However, somewhat different behaviors are observed. Raising the test temperature to 500° F reduces the tensile strength of the three tool steels by about 10 percent, the compressive yield by about 15 percent, the fatigue strength by as much as 20 percent (Halmo) and has essentially no effect on the tensile yield.

It is interesting to compare the 62  $R_c$  350° F mechanical properties of vacuum melt SAE 52100 with those of the tool steels at 500° F. According to table V the static tensile strength of the tool steels at 500° F is essentially equal to that of vacuum melt SAE 52100 at 350° F. However, the tool steels are definitely superior in regard to their tensile yield, compressive yield and the fatigue strength.

Comparison of static and fatigue properties. - Recently it has been proposed (12)(13) that the endurance limit and the elastic limit of hardened alloy steels may be similarly related to the hardness. Examination of this data reveals that there is very meager evidence to support the hypothesis. Furthermore, the results of the present investigation do not confirm the proposed relationship. Thus, referring to figures 7 and 8 the room temperature tension and compressive elastic limits of several SAE 52100 heats decrease at hardnesses above about 58  $R_c$ . However, the room temperature fatigue strength for the same heats, figure 14, remains essentially constant between 52  $R_c$  and 65  $R_c$ . It may be argued that true elastic limits were not established. However, the elastic limits previously reported (12) and (13) were obtained by essentially the same method used in this investigation and therefore may be subject to the same deficiencies.

A related observation is that vacuum melting definitely improves the room temperature and 350° fatigue strength of SAE 52100 (see figs. 14 and 15) but has little influence on the static properties (see figs. 7 and 8).

Apparently for SAE 52100 the factors which control the static and fatigue properties are fundamentally different and neither are as yet well understood.

### CONCLUSIONS

The complex nature of the phenomena observed and the limited number of tests performed render difficult the formulation of quantitative conclusions regarding the influence of alloy composition on the strength values. Furthermore, it is not considered that true elastic limits were determined nor were the 500° F fatigue strengths of the tool steels well established. However, for practical purposes the following conclusions appear substantiated:

1. Heat treated to yield hardnesses between about 50 and 58 R<sub>c</sub>, the room temperature tensile ultimate, tensile yield and the compressive yield strengths of SAE 52100 and the three tool steels increase nearly linearly with hardness. At a given hardness in this range only small strength differences are noted among the various steels.

2. At higher hardnesses the above relations at room temperature are generally maintained only for the compressive yield strength. The tensile static properties with the exception of Halmo exhibit a maximum at a certain hardness and then decrease with further increases in hardness. Thus, at hardnesses above about 60 R<sub>c</sub> Halmo appears to exhibit the highest tensile strength characteristics.

3. The room temperature fatigue strength ( $10^7$  -  $10^8$  cycles) at a hardness of 62  $R_C$  is nearly identical within the limits of scatter for vacuum.melt SAE 52100 and the three tool steels.

4. At a hardness level of 62  $R_C$  the tool steels tested at 500° F possess static and fatigue properties superior to those of SAE 52100 tested at 350° F.

5. The fatigue strengths of SAE 52100 at hardnesses between 50 and 65  $R_C$  are improved by induction vacuum melting.

6. A corresponding effect of vacuum melting is not observed for the static properties of SAE 52100.

7. No relation was found between any of the measured static properties and the fatigue characteristics.

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APPENDIX I: X-RAY DIFFRACTION STUDIES OF  
SEVERAL 52100 AND TOOL STEELS

Finish machined tensile specimens from two heats of SAE 52100 and the three tool steels were subjected to an X-ray diffraction study in an attempt to determine residual stresses of first and second order as well as the presence or absence of retained austenite and carbides. These studies were made on a General Electric XRD-5 diffraction unit with a proportional counter using vanadium oxide filtered chromium  $K\alpha$  radiation.

The interplanar spacings of the (211) planes parallel to the surface are shown in figure I-1 as a function of hardness and the (211) diffraction line width at one half intensity as a function of hardness in figure 2(a). Table IA gives the indications for retained austenite and carbides.

From figure 1(a) it can be seen that the  $d(211)$ -value increases for all steels with increasing hardness level. Since this  $d(211)$  value was determined from planes oriented parallel to the specimen surface an increase in residual compressive stress is indicated. Based on this concept a change of the  $d(211)$  value by  $0.0010 \overset{\circ}{\text{A}}$  represents a change in stress of approximately -30,000 psi. However, this figure can be used for order of magnitude type comparisons only.

According to figure II-2 the (211) line width also increases with increasing hardness level. Among the factors responsible for increase in diffraction line widths are microstrains, particle size, plastic deformation etc., the most significant contribution in the present case probably being microstrain. On this basis an increase of the line width at half

intensity of  $1^0$  corresponds to an increase of the microstrain level of approximately  $2 \times 10^{-3}$ . This figure can also serve for semi-quantitative evaluation only.

The amount of retained austenite, table IA, tended to increase somewhat at the higher hardness levels for all alloys. A similar increase was observed for the carbides except for the SAE 52100 vacuum melt and MV-1 which gave no carbide indications at any hardness level. The differences between the various alloys in respect to retained austenite and carbides is considerable. Only traces were found for the two heats of SAE 52100. In contrast, M-1 showed strong indications of retained austenite and carbides at the highest hardness level ( $65 R_C$ ). There does not, however, appear to be any definite correlation between these indications and the reported mechanical properties.

## APPENDIX II: COMPARISON OF BALL BEARING LIFE DATA WITH ROTATING BEAM FATIGUE RESULTS

Two of the SAE 52100 electric furnace heats, numbers 2 and 3 of the present investigation were evaluated in complete ball bearing tests at room temperature by the Physical Testing Laboratory of the Marlin-Rockwell Corp., Jamestown, New York. In addition, a SAE 52100 induction vacuum melt was also subjected to the bearing tests, however this was not the same heat presently reported. The authors are indebted to Mr. D. Lundquist of Marlin-Rockwell Corporation for supplying the ball bearing endurance data for comparison with the fatigue strengths reported in this investigation.

For the bearing tests inner rings, outer rings and balls of the 207-S size were fabricated by MRC. Test conditions were as follows: 2750 rpm, 1750 lbs radial load and jet applied lubrication with SAE No. 10 oil. The results of these tests are shown in figure II-1 on a Weibull plot. One characteristic of bearing performance which can be derived from this plot is the median life (50 percent failures). On the basis of this criterion the three heats rate as follows: vacuum melt, low residual and high residual. It will be noted from figure 14 that the same rating for heats numbers 2 and 3 was obtained from the rotating beam fatigue data at a hardness of 62 R<sub>C</sub>. Furthermore, both the rotating beam data and the ball bearing data reveal the superiority of vacuum melted material.

From this limited information the authors do not wish to suggest there is a definite correlation between rotating beam data and ball bearing performance. The general opinion in this country has not favored the existence of such a relation. However, the authors are not aware of any published systematic data which conclusively disprove its existence.

Bibliography

1. L. D. Cobb: "Effect of Vacuum Melting on Bearing Steels; SAE Preprint, March 1957.
2. G. C. Barnes and E. A. Ryder: "A Look at Some Turbine Bearing Problems; SAE Preprint No. 693, 1956.
3. P. H. Frith: "Fatigue Tests on Rolled Alloy Steels Made in Electric and Open Hearth Furnaces," Iron and Steel Institute, Special Report No. 50, 1954, London.
4. H. Styri: "Fatigue Strength of Ball Bearing Races and Heat Treated 52100 Steel Specimens," Proc. ASTM, vol. 51, 1951, p. 682.
5. J. T. Ransom: "The Effect of Inclusions on the Fatigue Strength of SAE 4340 Steels," Trans. ASM, vol. 46, 1954, p. 1254.
6. B. B. Muvdi, G. Sachs, and E. P. Klier: "Axial Load Fatigue Properties of High Strength Steels," Proc. ASTM, vol. 57, 1957, p. 655.
7. R. H. Butler, H. R. Bear, and T. L. Carter: "The Effect of Fiber Orientations on Ball Failures Under Rolling Contact Conditions" NACA Tech. Note No. 3933, Feb. 1957.
8. A. H. Grobe and G. A. Roberts: "The Bend Test for High Speed Steel," Trans. ASM, vol. 40, 1948, p. 435.
9. J. C. Hamaker, V. C. Strang, and G. A. Roberts: "Bend-Tensile Relationships for Tool Steels at High Strength Levels," Trans. ASM, vol. 49, 1957, p. 550.
10. P. H. Frith: "Fatigue of Wrought High-Tensile Alloy Steels," International Conference on Fatigue of Metals, Institution of Mechanical Engineers, London, 1956.

11. G. Sachs: "Survey of Low Alloy High Strength Steels Heat Treated to High Strength Levels" Pt. 2: Fatigue WADC Tech. Report 53-254, 1954.
12. H. Muir, B. L. Averbach, and M. Cohen: "The Elastic Limit and Yield Behavior of Hardened Steels" Trans. ASM, vol. 47, 1955, p. 380.
13. C. H. Shih, B. L. Averbach, and M. Cohen: "Some Effects of Silicon on the Mechanical Properties of High Strength Steels," Trans. ASM, vol. 48, 1956, p. 86.
14. M. H. Jones and W. F. Brown, Jr.: "An Axial Loading Fixture" ASTM Bulletin, Jan. 1956, p. 53.
15. D. J. McAdam, Jr. and R. W. Mebs: "Tensile Elastic Properties of Typical Stainless Steels and Nonferrous Metals as Affected by Plastic Deformation and by Heat Treatment," NACA Report No. 696, 1940.
16. Physical and Electrical Properties of Fine Resistance Wire; Driver-Harris Co., Tech. Bulletin No. 157, New Jersey.
17. W. R. Campbell: "Performance Tests of Wire Strain Gages, I: Calibration Factors in Tension" NACA TN 954 (1944).
18. W. R. Campbell: Ibid, NACA TN 978 (1945).
19. L. J. Klingler, C. C. Chow, and G. Sachs: "Flow and Fracture Characteristics of a Die Steel at High Hardness Levels" Trans. AIMME, vol. 185, 1949, p. 927.
20. H. Sigwart: "Influence of Residual Stresses on the Fatigue Limit," International Conference on the Fatigue of Metals, Institution of Mechanical Engineers, London, 1956.
21. R. L. Matison: "Fatigue Residual Stresses and Cold Work," Ibid.

22. L. P. Tarasov, W. S. Hyler, and H. R. Letner: "Effect of Grinding Conditions and Resultant Residual Stresses on the Fatigue Strength of Hardened Steel," Proc. ASTM, vol. 57, 1957, p. 601.
23. L. P. Tarasov and H. S. Grover: "Effects of Grinding and Other Finishing Processes on the Fatigue Strength of Hardened Steel," Proc. ASTM, vol. 50, 1950, p. 668.
24. M. F. Garwood, H. H. Zurburg, and M. A. Erickson: "Correlation of Laboratory Tests and Service Performance," Interpretations of Tests and Correlations with Service, ASM, 1951.
25. W. S. Hyler, L. P. Tarasov, and R. J. Favor: "Distribution of Fatigue Failures in Flat Hardened Steel Test Bars," Proc. ASTM, vol. 58, 1958, p.
26. F. B. Stulen, H. N. Cummings, and W. C. Schulte: "Relation of Inclusions to the Fatigue Properties of High Strength Steels," International Conference on Fatigue of Metals, Institution of Mechanical Engineers, London, 1956.
27. W. L. Starkey, S. M. Marco, and R. R. Gatts: "Statistical Evaluation of Endurance Limit Among Several Heats of Propeller Type Steel," WADC TR 55-483 (ASTIA No. AD 97190) Aug. 1956.
28. R. H. Butler, H. R. Bear, and T. L. Carter: "Effect of Fiber Orientations on Ball Failures Under Rolling Contact Conditions," NACA TN 3933, Feb. 1957.
29. H. R. Bear and R. H. Butler: "Preliminary Metallographic Studies of Ball Fatigue Under Rolling Contact Conditions," NACA TN 3925, March 1957.

TABLE I. - CHEMICAL COMPOSITIONS FOR  
THE INVESTIGATED STEELS

| ALLOY   | C    | Mn   | P     | S     | Si   | Cr   | V    | W    | Mo   | Cu   | Ni   |
|---|------|------|-------|-------|------|------|------|------|------|------|------|
| SAE 52100*<br>Electric Furnace<br>Heat No. 1  | 1.03 | 0.32 | 0.01  | 0.02  | 0.29 | 1.49 | -    | -    | 0.01 | 0.05 | 0.08 |
| SAE 52100**<br>Electric Furnace<br>Heat No. 2 | 1.02 | 0.41 | 0.009 | 0.012 | 0.30 | 1.43 | -    | -    | 0.02 | 0.11 | 0.08 |
| SAE 52100**<br>Electric Furnace<br>Heat No. 3 | 1.06 | 0.34 | 0.012 | 0.009 | 0.30 | 1.43 | -    | -    | 0.02 | 0.12 | 0.13 |
| SAE 52100*<br>Induction Vacuum                | 1.05 | 0.37 | 0.002 | 0.007 | 0.26 | 1.51 | -    | -    | tr   | 0    | 0.02 |
| Halmo*<br>Induction Vacuum                    | 0.59 | 0.31 | 0.005 | 0.007 | 1.10 | 4.79 | 0.51 | -    | 5.22 | -    | -    |
| M-1 (AISI TMO)*<br>Induction Vacuum           | 0.80 | 0.25 | 0.004 | 0.007 | 0.32 | 3.74 | 1.15 | 1.53 | 8.54 | 0.01 | 0.07 |
| MV-1 (AISI M-50)*<br>Induction Vacuum         | 0.81 | 0.26 | 0.004 | 0.007 | 0.14 | 3.97 | 1.07 | 0.01 | 4.29 | 0.01 | 0.05 |

\*Crucible Steel Co., Syracuse, New York.

\*\*Marlin Rockwell Corp., Jamestown, New York.

TABLE IA. - INDICATIONS FOR RETAINED  
AUSTENITE AND CARBIDES

| Alloy      | Code* | Rc 50 | Rc 54 | Rc 58 | Rc 62 | Rc 65 |
|------------|-------|-------|-------|-------|-------|-------|
| 52100      | c     | -     | -     | -     | -     | tr    |
| Heat No. 1 | A     | -     | -     | -     | tr    | tr    |
| 52100      | c     | -     | -     | -     | -     | -     |
| Induction  | A     | -     | -     | -     | tr    | tr    |
| Vacuum     |       |       |       |       |       |       |
| Halmo      | c     | -     | -     | tr    | w     | w     |
|            | A     | -     | -     | tr    | w     | w     |
| M-1        | c     | s     | s     | s     | s     | s     |
|            | A     | -     | tr    | tr    | tr    | s     |
| MV-1       | c     | -     | -     | -     | -     | -     |
|            | A     | -     | w     | w     | w     | w     |

\*Code

c = Carbide indication

A = Austenite indication

s = strong

w = weak

tr = trace

TABLE II. - INCLUSION COUNT ACCORDING  
TO JK CHARTS (ASTM E 45-51)\*

| Alloy                         | Thin |       |     |     | Heavy |     |     |     |
|-------------------------------|------|-------|-----|-----|-------|-----|-----|-----|
|                               | A    | B     | C   | D   | A     | B   | C   | D   |
| SAE 52100<br>Heat No. 1       | 2.0  | 1.5   | 3.0 | 2.0 | 1.0   | 1.0 | 1.0 | 1.5 |
| SAE 52100<br>Heat No. 2       | 2.0  | 1.5   | 2.0 | 3.0 | 0.5   | 1.0 | 1.0 | 1.0 |
| SAE 52100<br>Heat No. 3       | 1.5  | 3.0   | 2.0 | 2.0 | 0     | 1.0 | 1.0 | 1.5 |
| SAE 52100<br>Induction Vacuum | 0.5  | 2.0** | 0.5 | 1.0 | 0     | 0   | 0   | 0   |
| Halmo                         | 0.5  | 2.0   | 0.5 | 2.0 | 0     | 0   | 0   | 0.5 |
| M-1                           | 0.5  | 1.5   | 0.5 | 2.0 | 0     | 0.5 | 0   | 0.5 |
| MV-1                          | 0    | 1.0   | 0   | 1.5 | 0     | 0   | 0   | 0   |

\*Determined by Allegheny Ludlum Corp., Pittsburgh, Pa.

\*\*One field, average rating - 1.0.

TABLE III. - HEAT TREATMENT

SCHEDULES FOR SAE 52100\*

| Alloy                         | Hardness,<br>R <sub>C</sub> | Heat treatment                     |        |                                     |                            |
|-------------------------------|-----------------------------|------------------------------------|--------|-------------------------------------|----------------------------|
|                               |                             | Austen-<br>itizing<br>temp.,<br>°F | Quench | 1st Temper<br>temp., time,<br>°F hr | 2nd Temper<br>temp.,<br>°F |
| SAE 52100<br>Heat No. 1       | 50                          | 1535                               | Oil    | 320 0.5                             | 775                        |
|                               | 54                          |                                    |        | 320 0.5                             | 600                        |
|                               | 58                          |                                    |        | 320 0.5                             | 525                        |
|                               | 62                          |                                    |        | 320 0.5                             | 350                        |
|                               | 65                          |                                    |        | 300 0.33                            | -                          |
| SAE 52100<br>Heat No. 2       | 50                          | 1535                               | Oil    | 320 0.5                             | 785                        |
|                               | 54                          |                                    |        | 320 0.5                             | 700                        |
|                               | 58                          |                                    |        | 320 0.5                             | 545                        |
|                               | 62                          |                                    |        | 320 0.5                             | 365                        |
|                               | 65                          |                                    |        | 300 0.33                            | -                          |
| SAE 52100<br>Heat No. 3       | 50                          | 1535                               | Oil    | 320 0.5                             | 785                        |
|                               | 54                          |                                    |        | 320 0.5                             | 700                        |
|                               | 58                          |                                    |        | 320 0.5                             | 545                        |
|                               | 62                          |                                    |        | 320 0.5                             | 365                        |
|                               | 65                          |                                    |        | 300 0.33                            | -                          |
| SAE 52100<br>Induction Vacuum | 50                          | 1535                               | Oil    | 320 0.5                             | 750                        |
|                               | 54                          |                                    |        | 320 0.5                             | 625                        |
|                               | 58                          |                                    |        | 320 0.5                             | 500                        |
|                               | 62                          |                                    |        | 320 0.5                             | 340                        |
|                               | 65                          |                                    |        | 300 0.33                            | -                          |

\*Heat treated by Marlin Rockwell Corp., Jamestown, New York.

TABLE IV. - HEAT TREATMENT PROCEDURES  
FOR TOOL STEELS<sup>1,2</sup>

| Alloy | Type of heat treatment | Heat treatment                     |        |                                 |                                       | Hardness<br>R <sub>C</sub><br>approx. |
|-------|------------------------|------------------------------------|--------|---------------------------------|---------------------------------------|---------------------------------------|
|       |                        | Austen-<br>itizing<br>temp.,<br>°F | Quench | 1st 2 hr<br>temper temp.,<br>°F | 2nd 2 hr<br>temper temp.,<br>°F       |                                       |
| Halmo | Experi-<br>mental      | 2100                               | Air    | 1000                            | 1145<br>1115<br>1090<br>1060<br>----- | 50<br>54<br>58<br>62<br>65            |
| Halmo | Commer-<br>cial        | 2100                               | Oil    | 1000                            | 1000                                  | 62                                    |
| M-1   | Experi-<br>mental      | 2200                               | Oil    | 1000                            | 1200<br>1170<br>1150<br>1120<br>----- | 50<br>54<br>58<br>62<br>65            |
| M-1   | Commer-<br>cial        | 2200                               | Oil    | 1000                            | 1000                                  | 62                                    |
| MV-1  | Experi-<br>mental      | 2050                               | Oil    | 1000                            | 1200<br>1160<br>1125<br>1060<br>----- | 50<br>54<br>58<br>62<br>65            |
| MV-1  | Commer-<br>cial        | 2050                               | Oil    | 1000                            | 1000                                  | 62                                    |

<sup>1</sup>Heat treated by Marlin Rockwell Corp., Jamestown, New York.

<sup>2</sup>All specimens preheated at 1500° F.

TABLE V. - EFFECTS OF ELEVATED TEMPERATURE ON MECHANICAL  
PROPERTIES OF VACUUM-MELTED BEARING STEELS AND  
SAE 52100 VACUUM MELT AT A HARDNESS OF 62 R<sub>C</sub>

| Alloy  | Temperature,<br>°F | Tensile          |               | Compressive<br>yield,<br>psi | Fatigue strength,<br>10 <sup>7</sup> cycles psi |
|--------|--------------------|------------------|---------------|------------------------------|---|
|        |                    | Strength,<br>psi | Yield,<br>psi |                              |   |
| 52100  | Room<br>350        | 340,000          | 240,000       | 400,000                      | 130,000   |
|        |                    | 340,000          | 260,000       | 290,000                      | 95,000  |
| Halmo* | Room<br>500        | 370,000          | 310,000       | 410,000                      | 140,000   |
|        |                    | 335,000          | 310,000       | 340,000                      | 110,000   |
| M-1*   | Room<br>500        | 370,000          | 310,000       | 420,000                      | 130,000   |
|        |                    | 350,000          | 300,000       | 355,000                      | 110,000   |
| MV-1*  | Room<br>500        | 370,000          | 295,000       | 340,000                      | 125,000   |
|        |                    | 335,000          | 300,000       | 340,000                      | 100,000   |

\*Commercial heat treatment, see table IV.

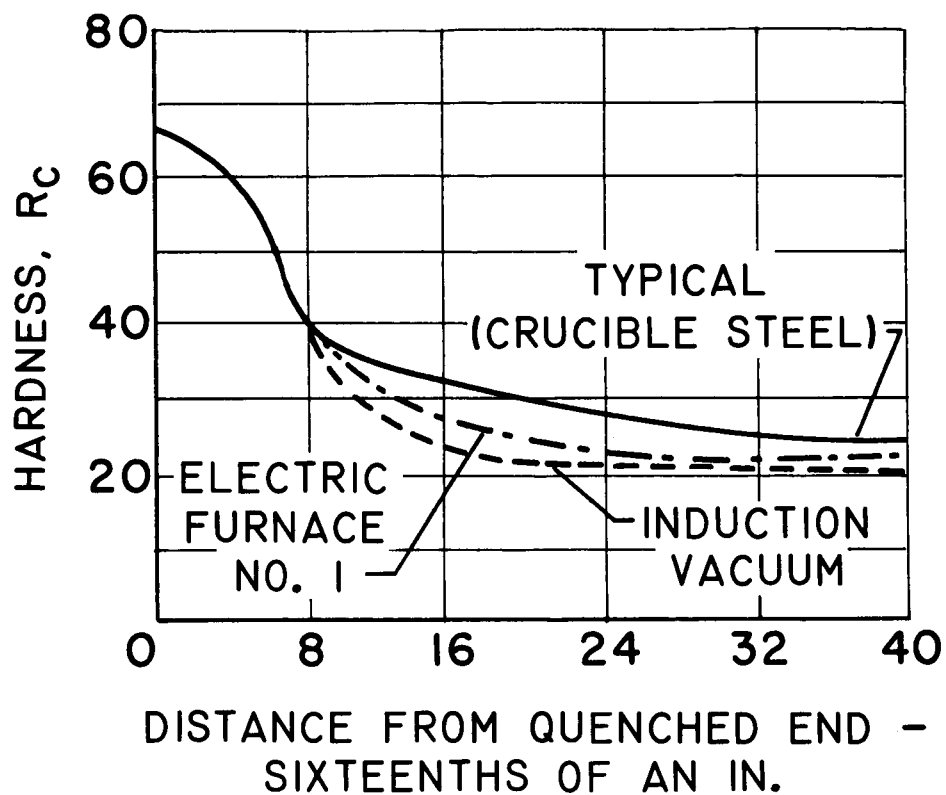
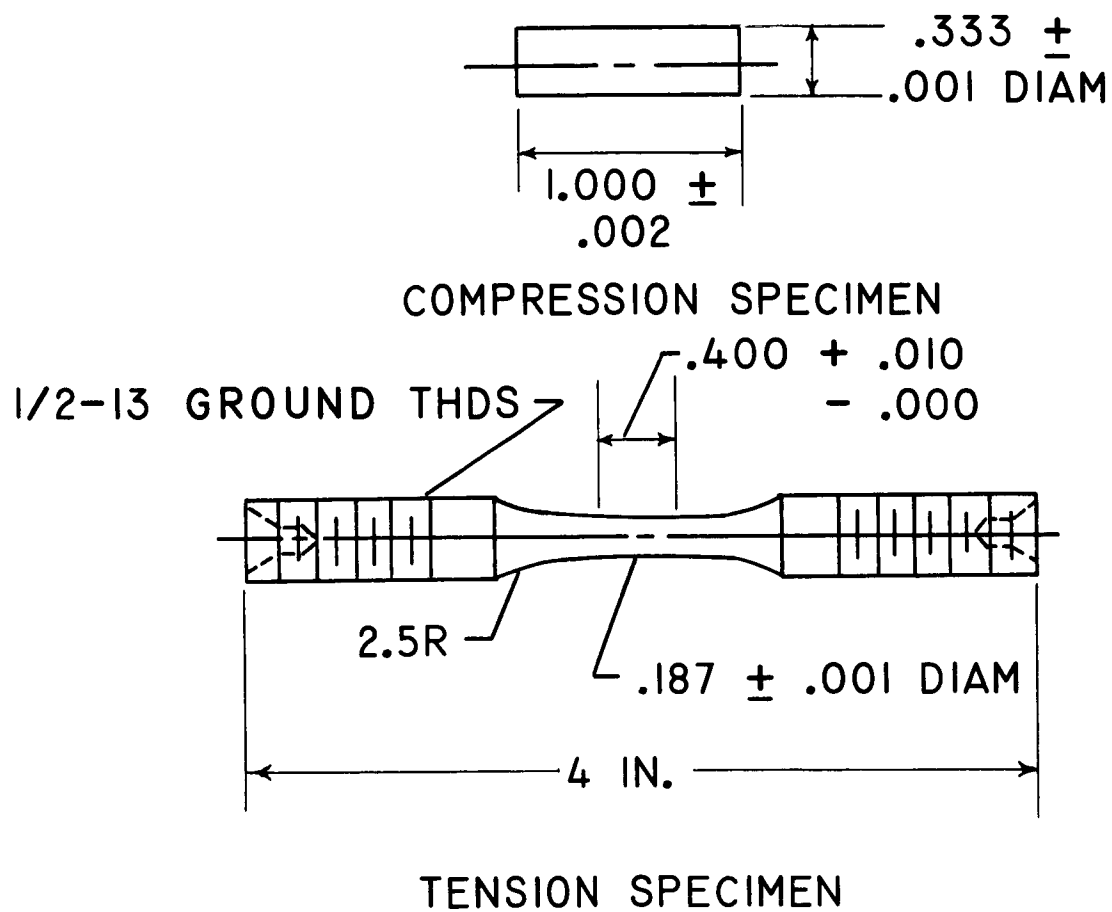


Fig. 1. - Hardenability of two SAE 52100 heats.



NOTE : THREADS TO BE CONCENTRIC WITH  
CENTERLINE OF TEST SECTION WITH IN  
10.0005 IN.

Fig. 2. - Tensile and compression specimens.

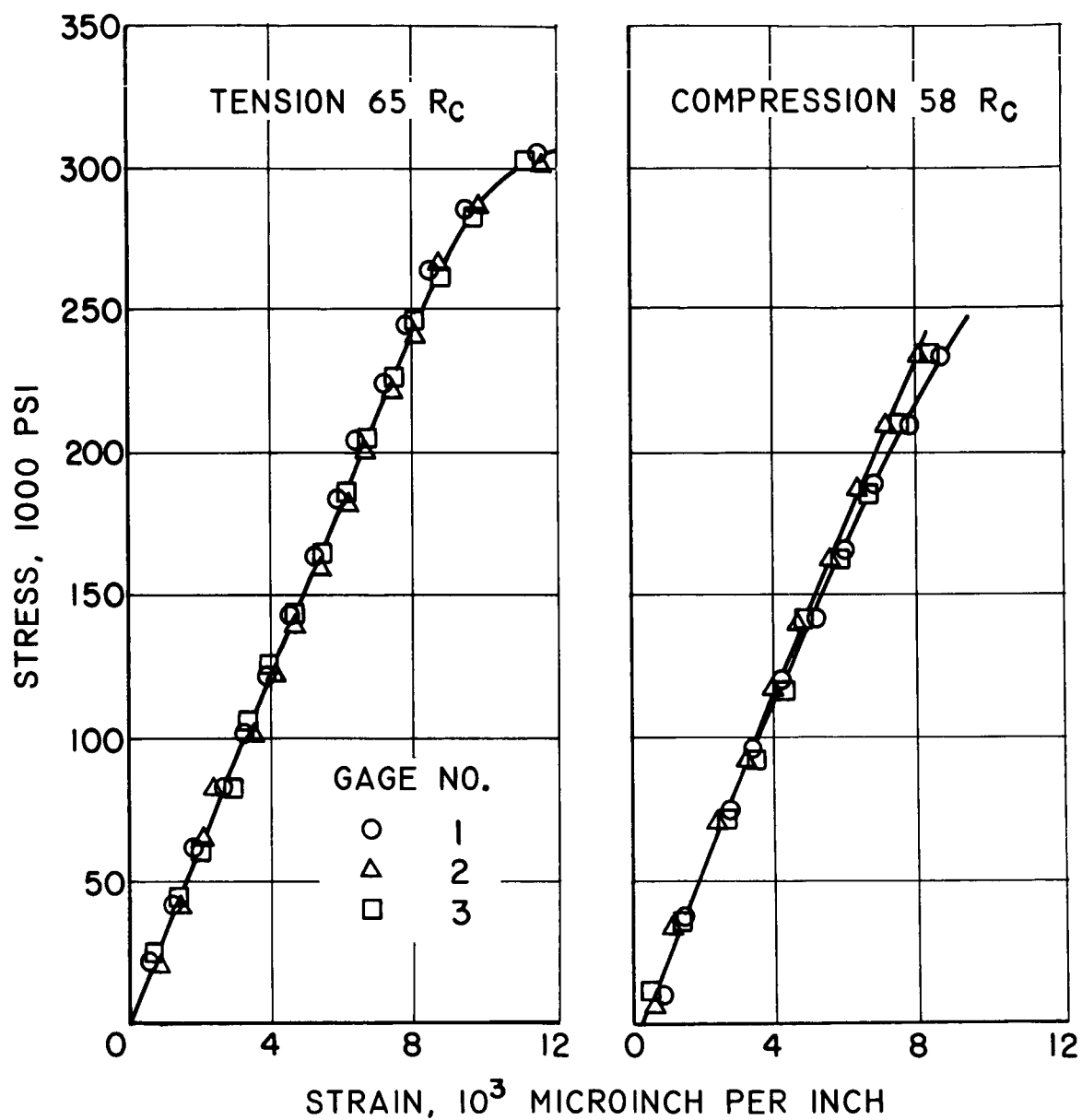
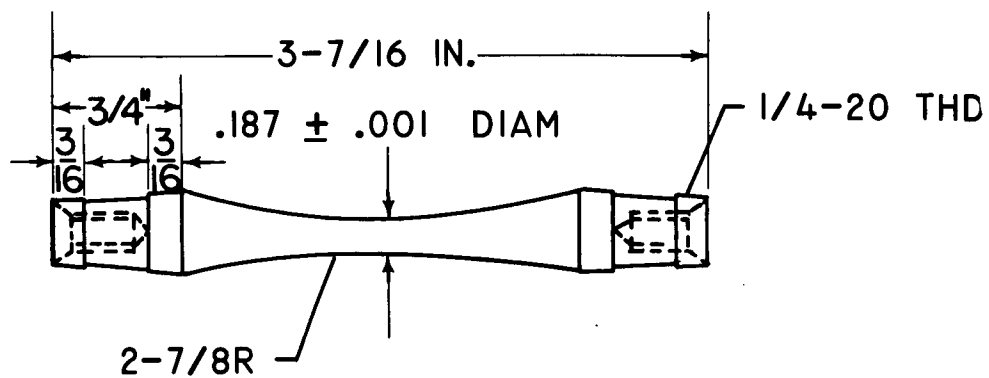
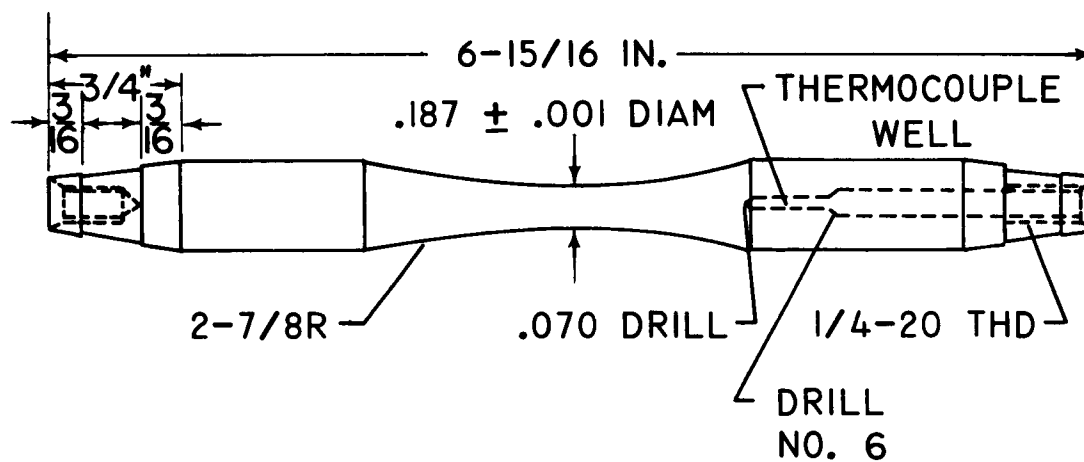


Fig. 3. - Alinement checks for tension and compression specimens of SAE 52100 heat no. 1.



ROOM TEMPERATURE FATIGUE SPECIMEN



ELEVATED TEMP FATIGUE SPECIMEN

Fig. 4. - Room and elevated temperature rotating bending fatigue specimens.

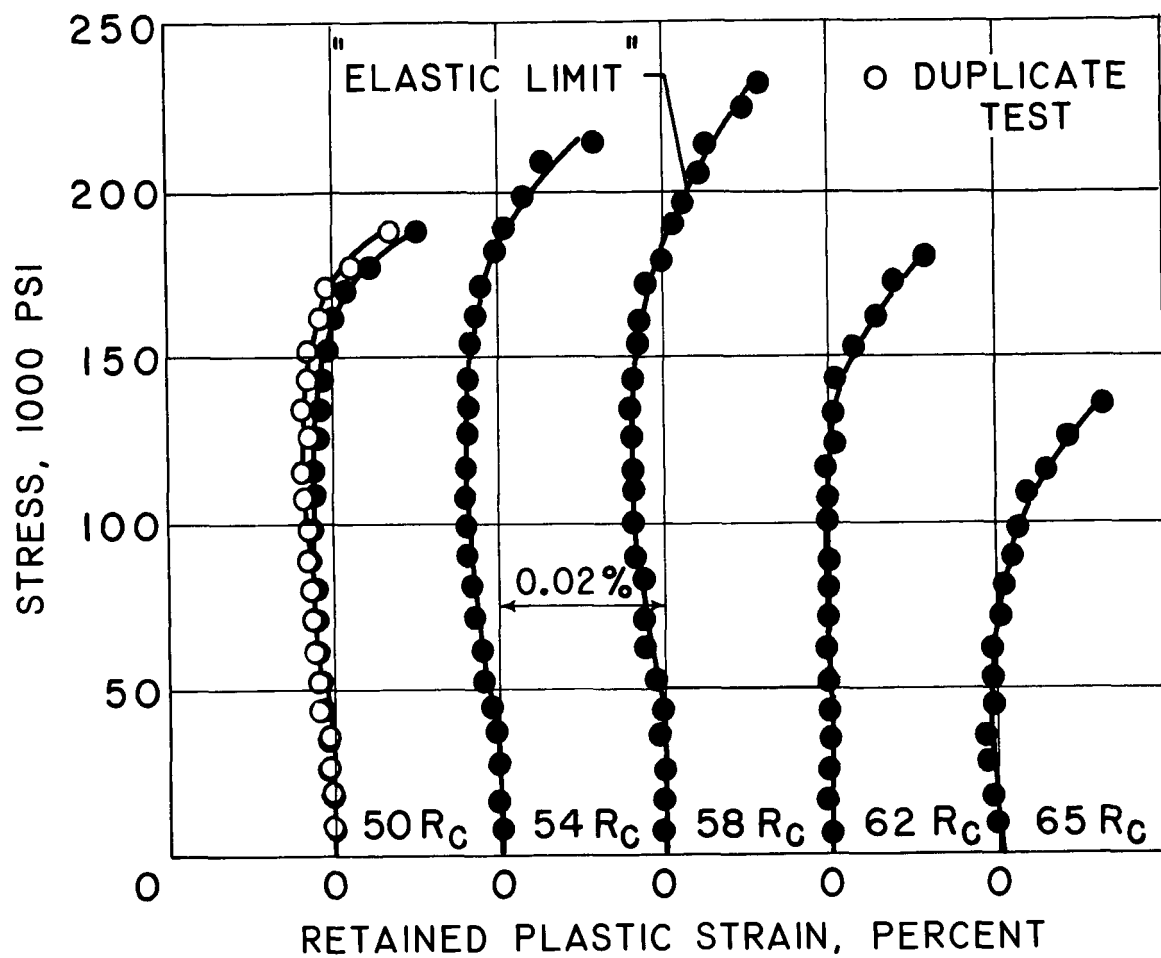


Fig. 5. - Example of load release curves in tension for SAE 52100 heat no. 3.

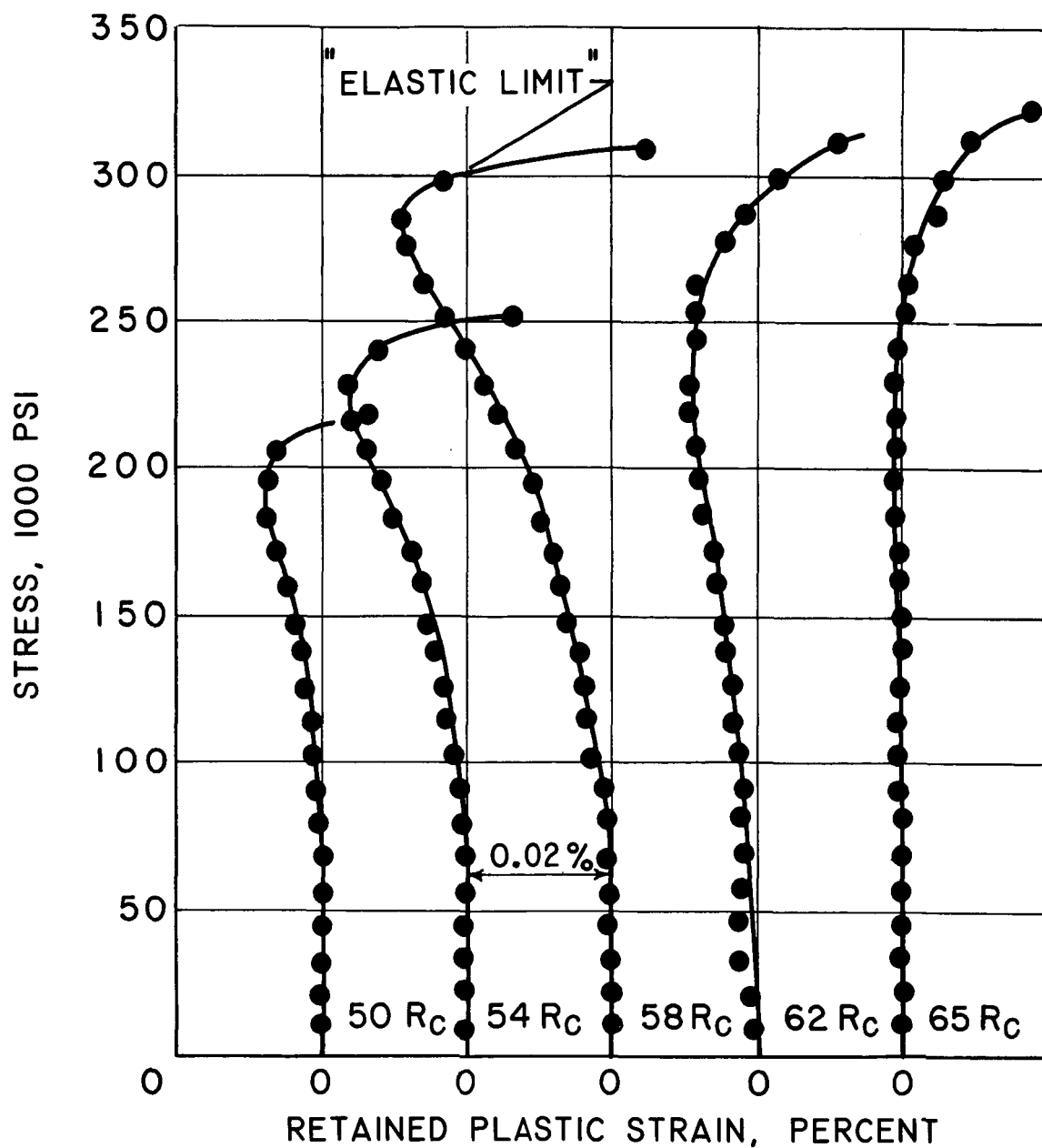


Fig. 6. - Example of load release curves in compression for SAE 52100 heat no. 3.

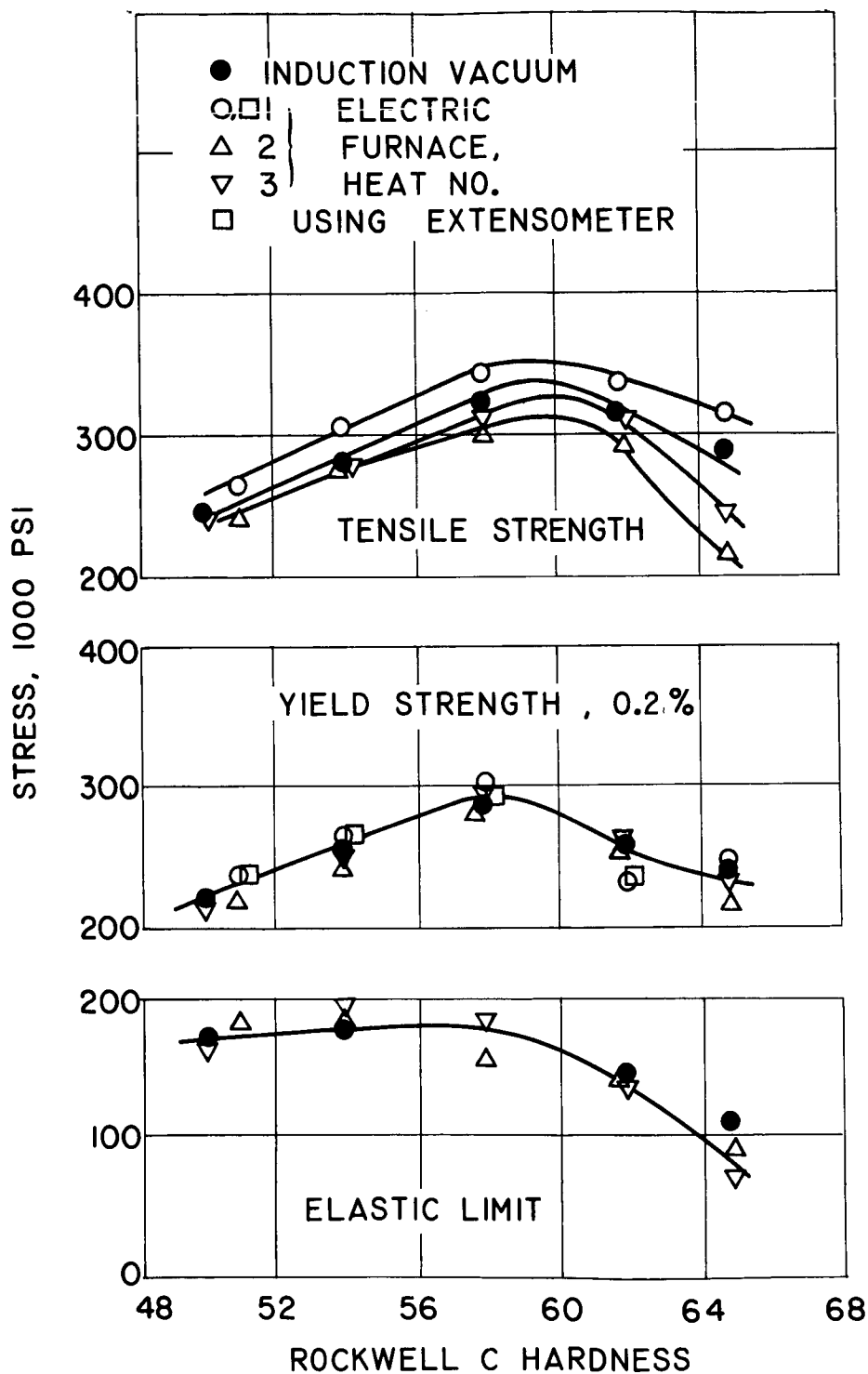


Fig. 7. - Room temperature tension characteristics for various heats of SAE 52100. Values shown are average of two or more tests unless indicated.

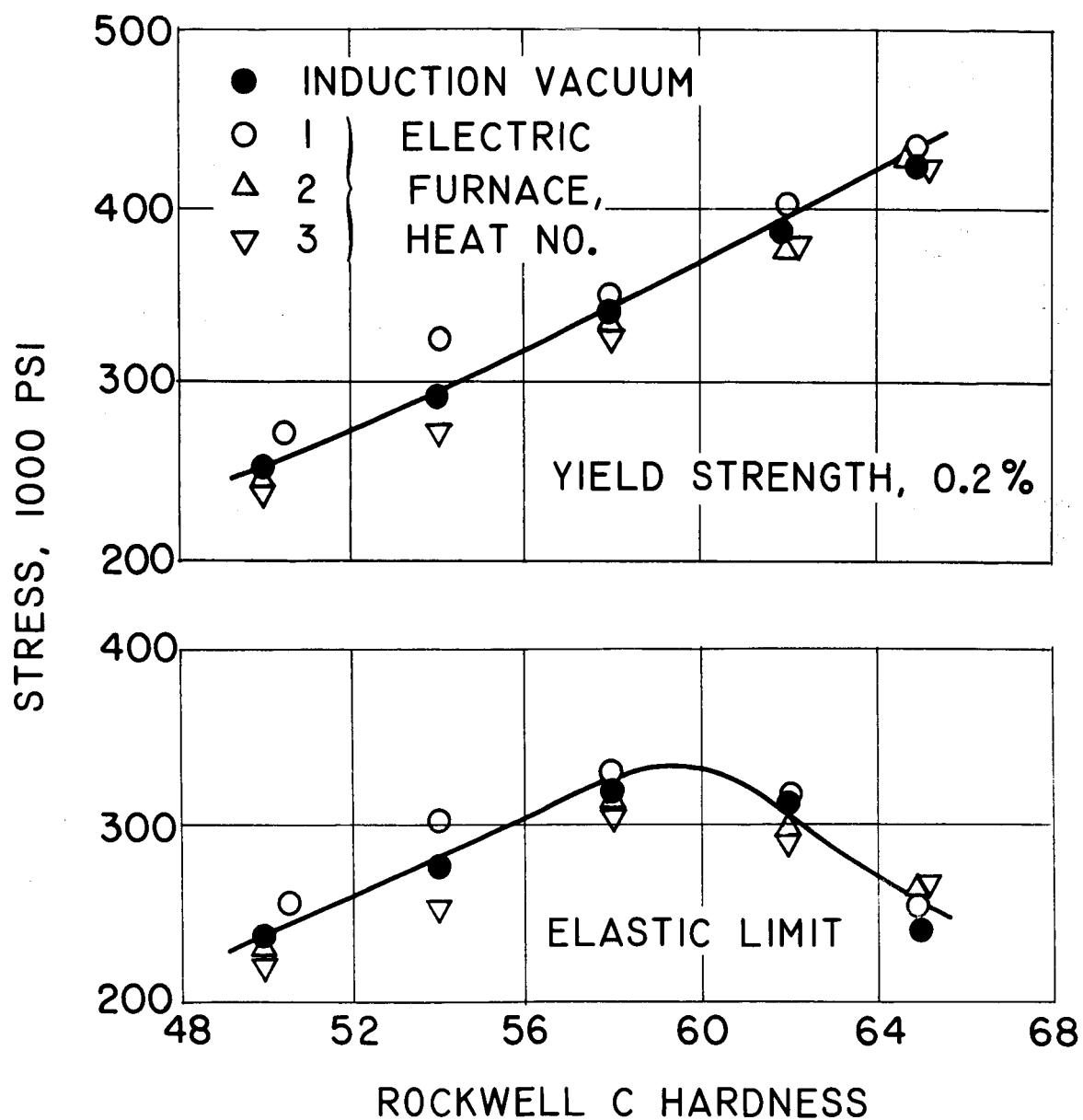


Fig. 8. - Room temperature compression characteristics for various heats of SAE 52100. Values shown are average of two or more tests unless indicated.

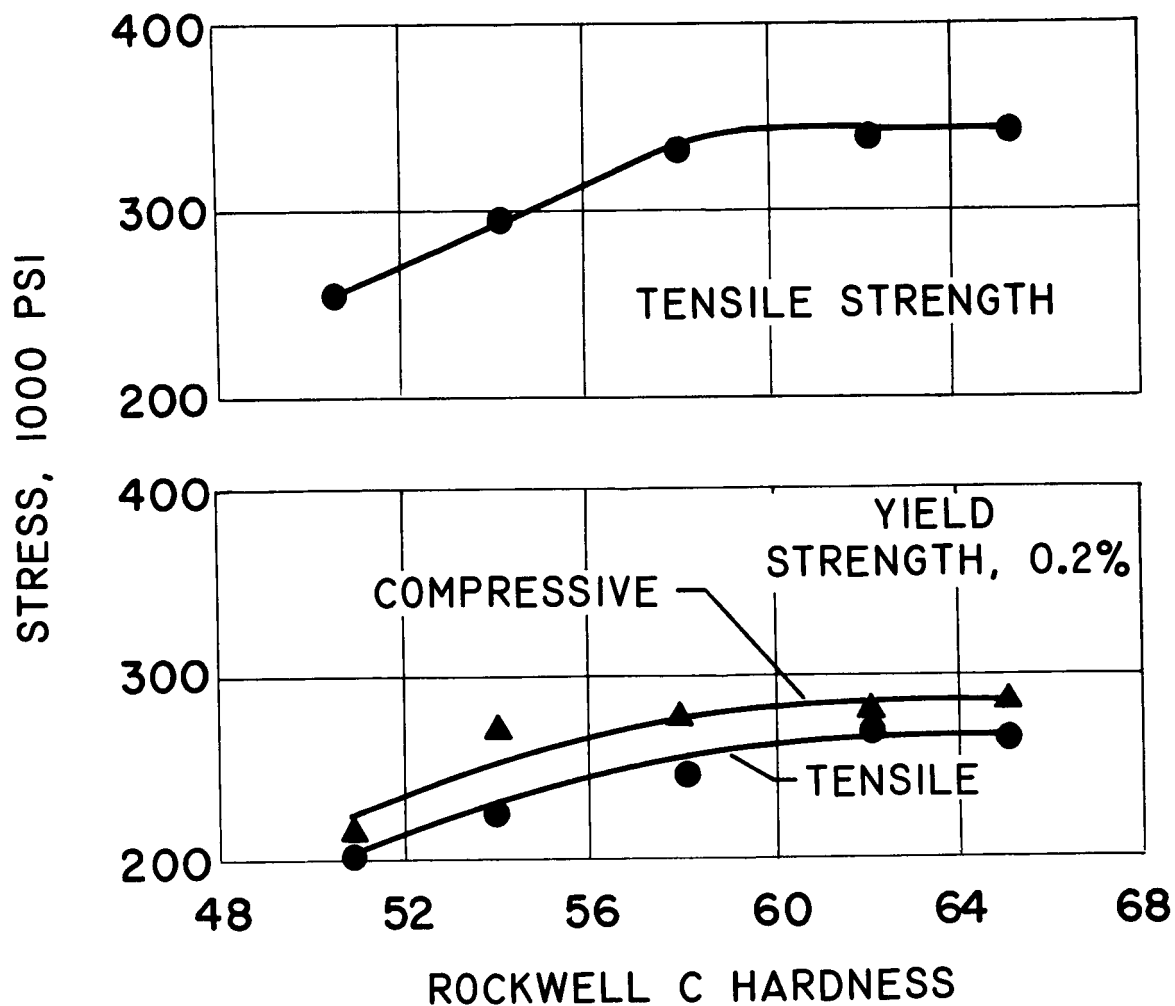


Fig. 9. - 350° F Tension and compression characteristics of SAE 52100 heat no. 1. Values shown are average of two or more tests unless indicated.

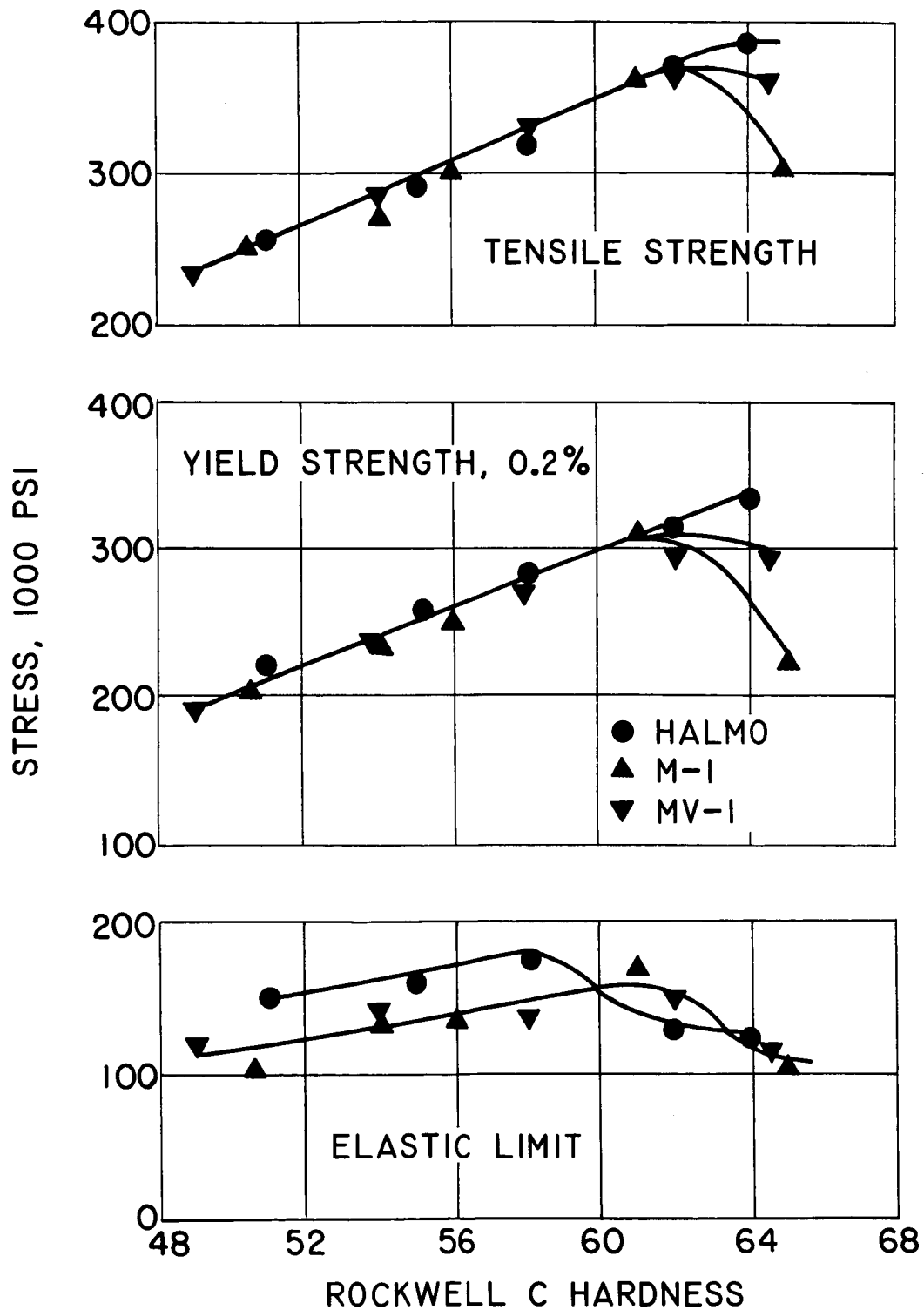


Fig. 10. - Room temperature tension characteristics for the various tool steels. Values shown are average of two or more tests unless indicated.

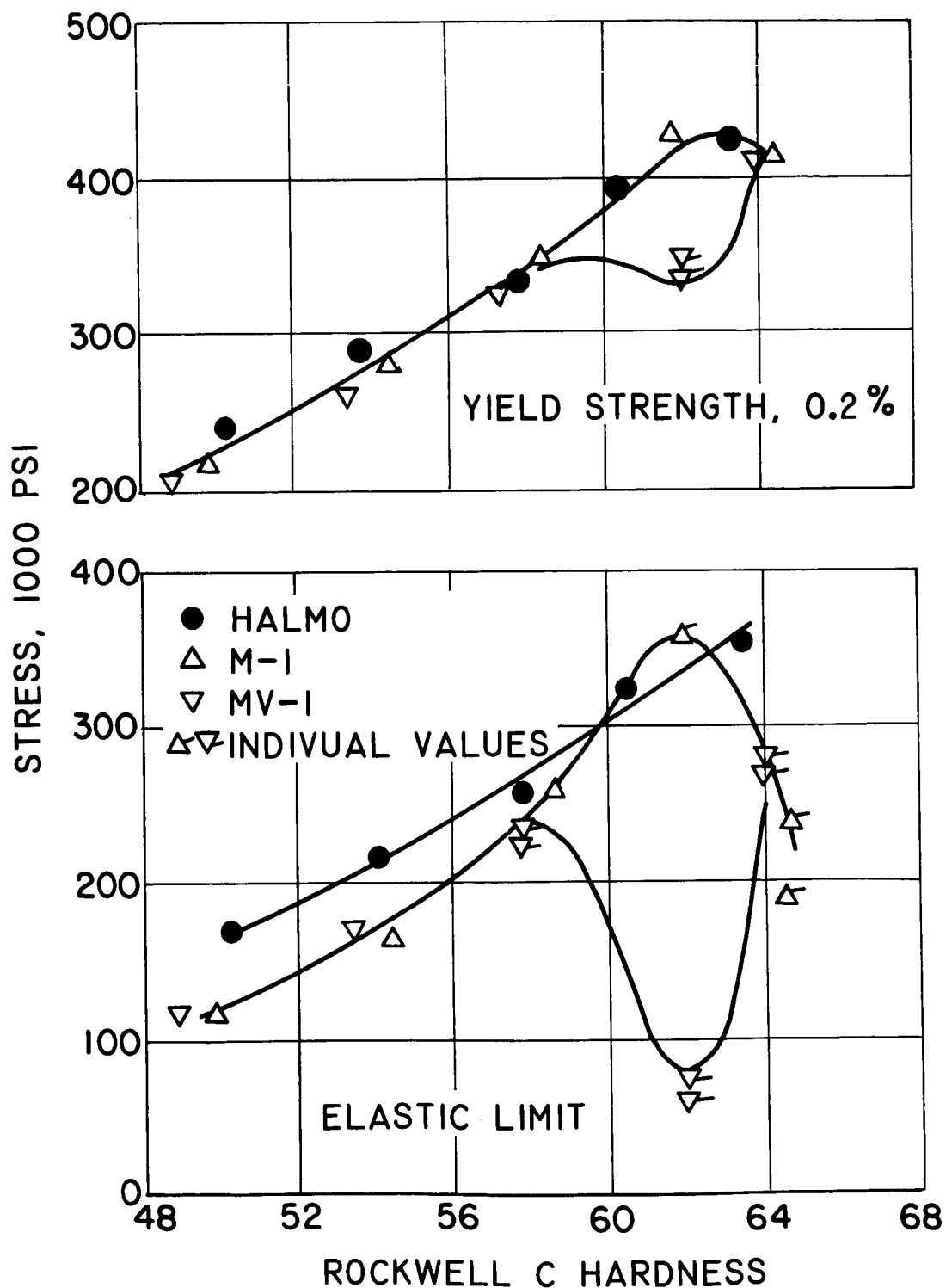


Fig. 11. - Room temperature compression characteristics for the various tool steels. Values shown are average of two or more tests unless indicated.

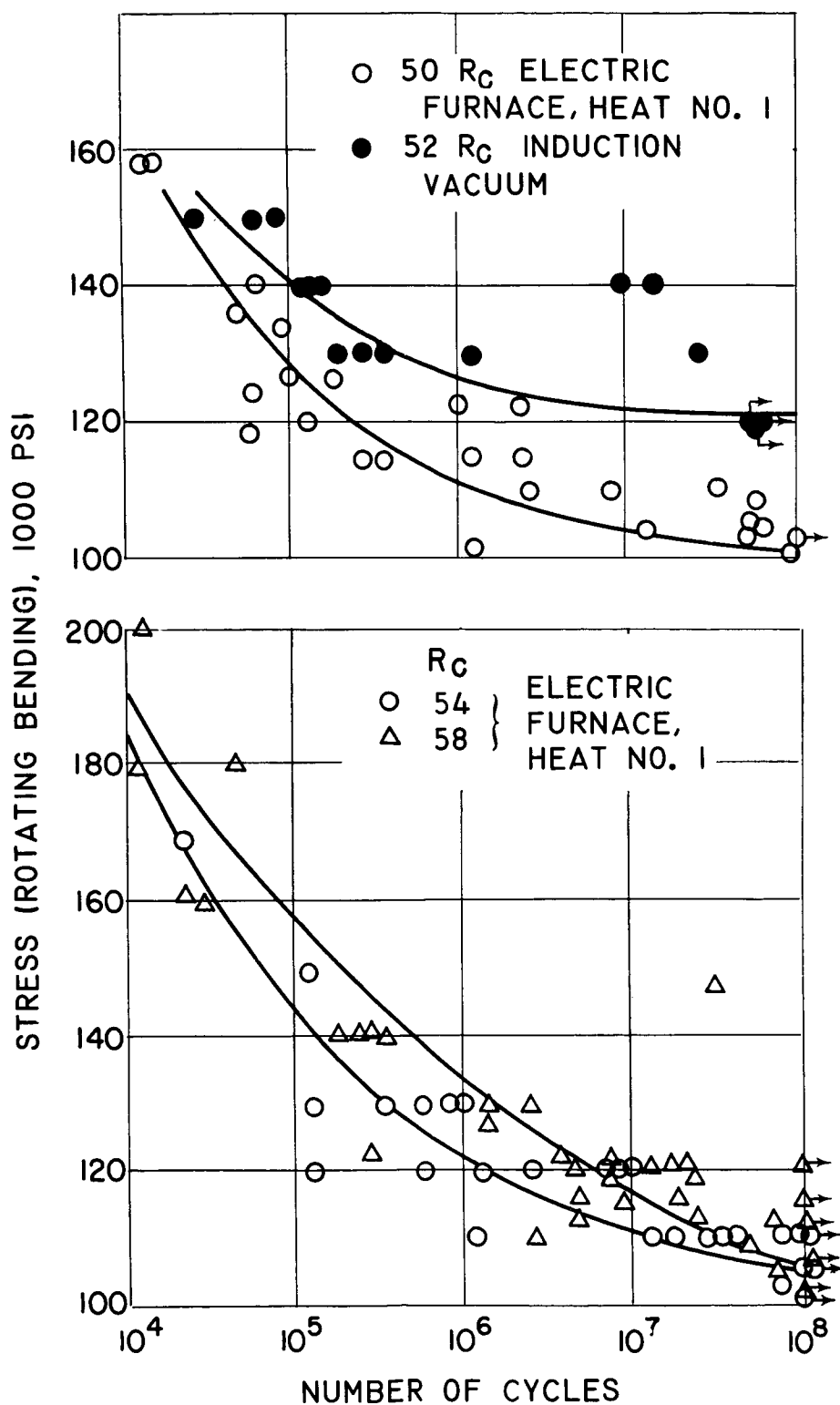


Fig. 12. - Room temperature S-N curves for two heats of SAE 52100 at several hardness levels.

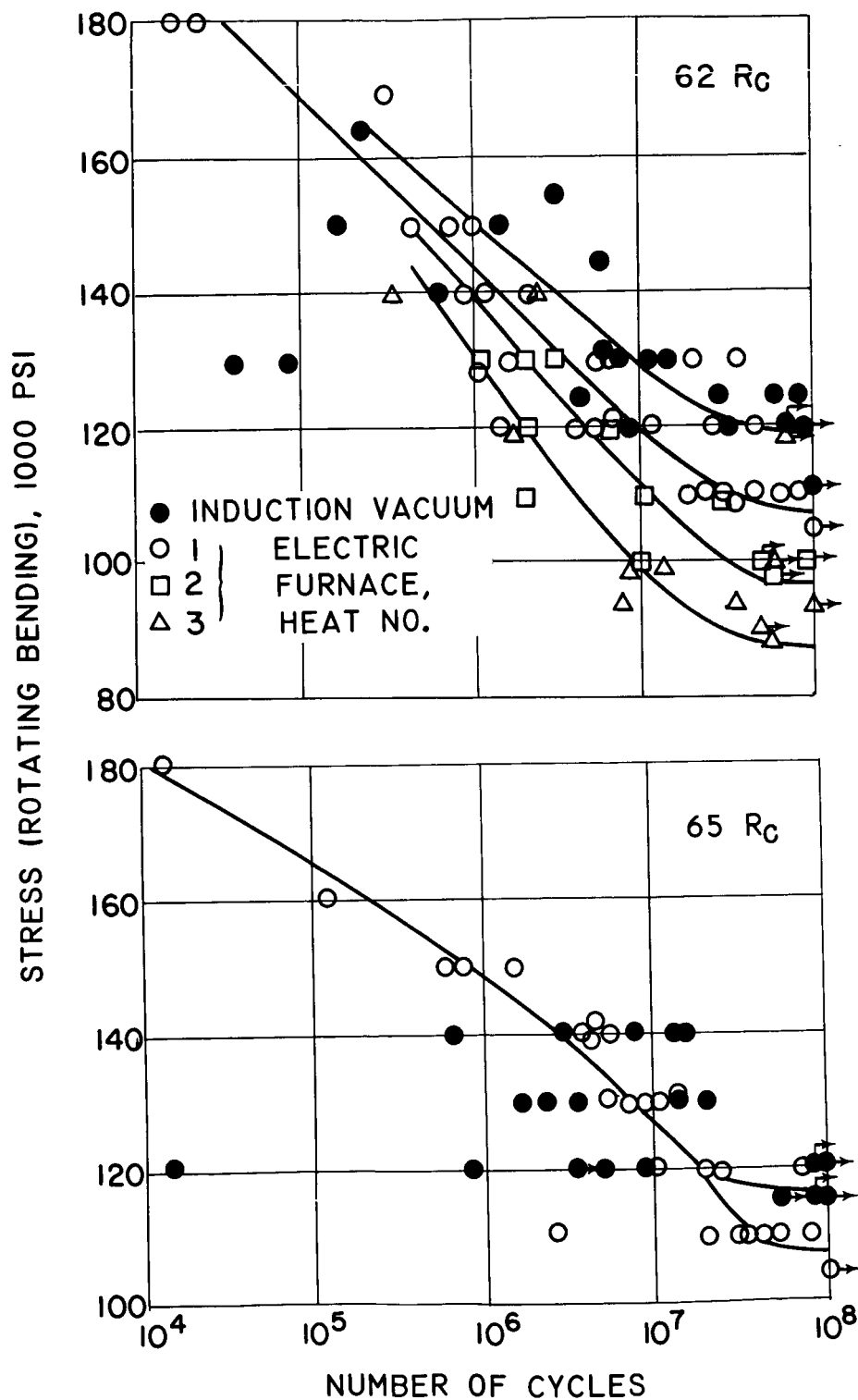


Fig. 13. - Room temperatures S-N curves for several heats of SAE 52100 tested at two hardness levels.

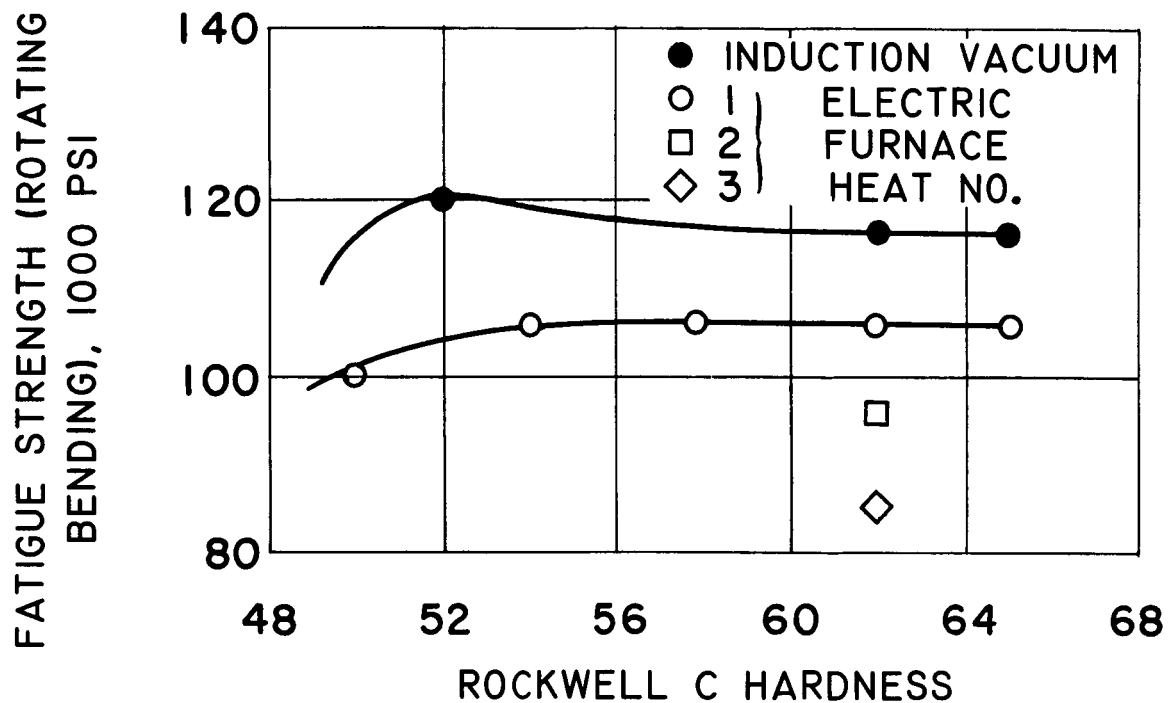


Fig. 14. - Comparison of room temperature fatigue strengths at  $10^8$  cycles for the various heats of SAE 52100 as a function of hardness level.

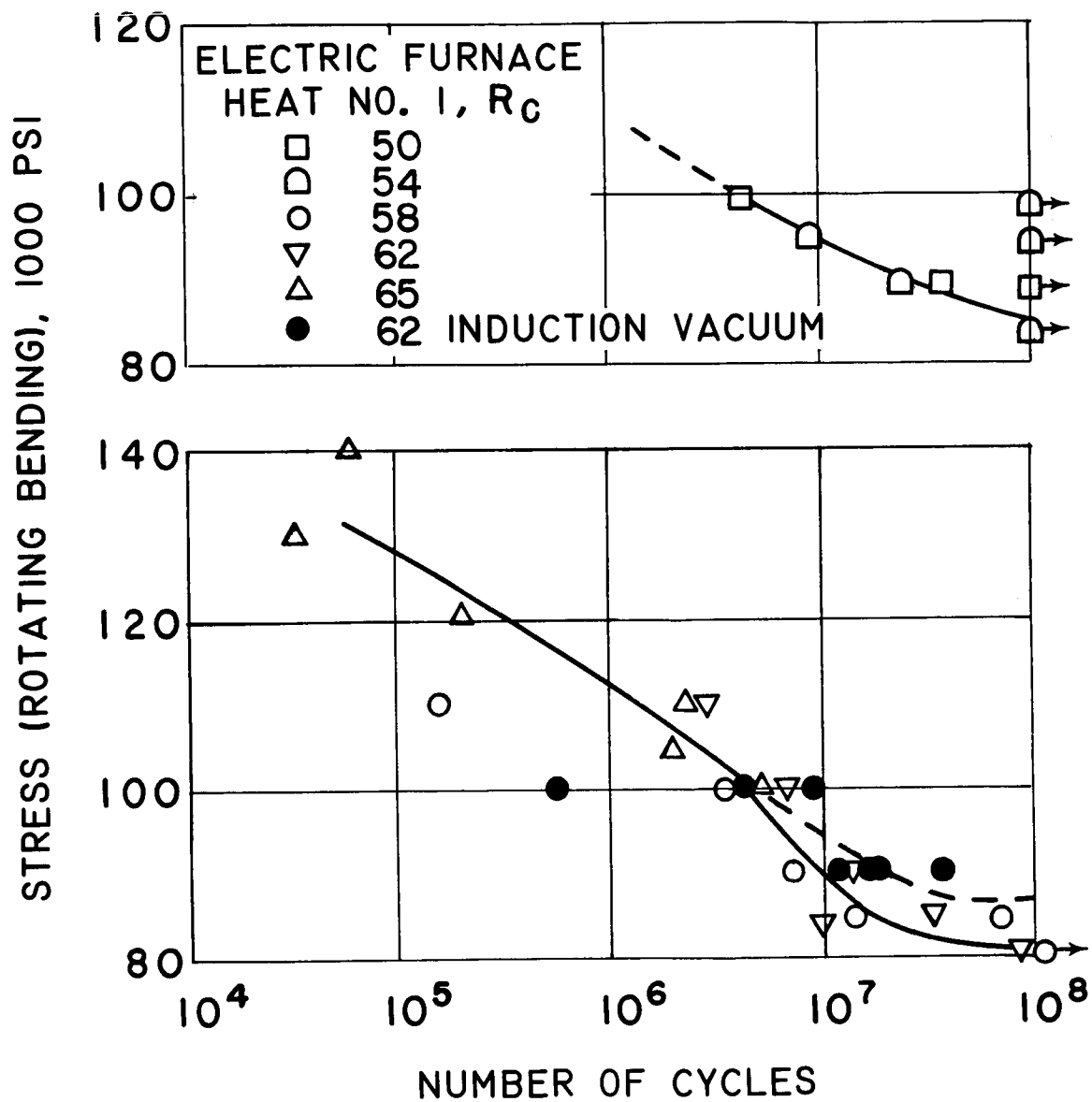


Fig. 15. - 350° F S-N curves for two heats of SAE 52100 tested at several hardness levels.

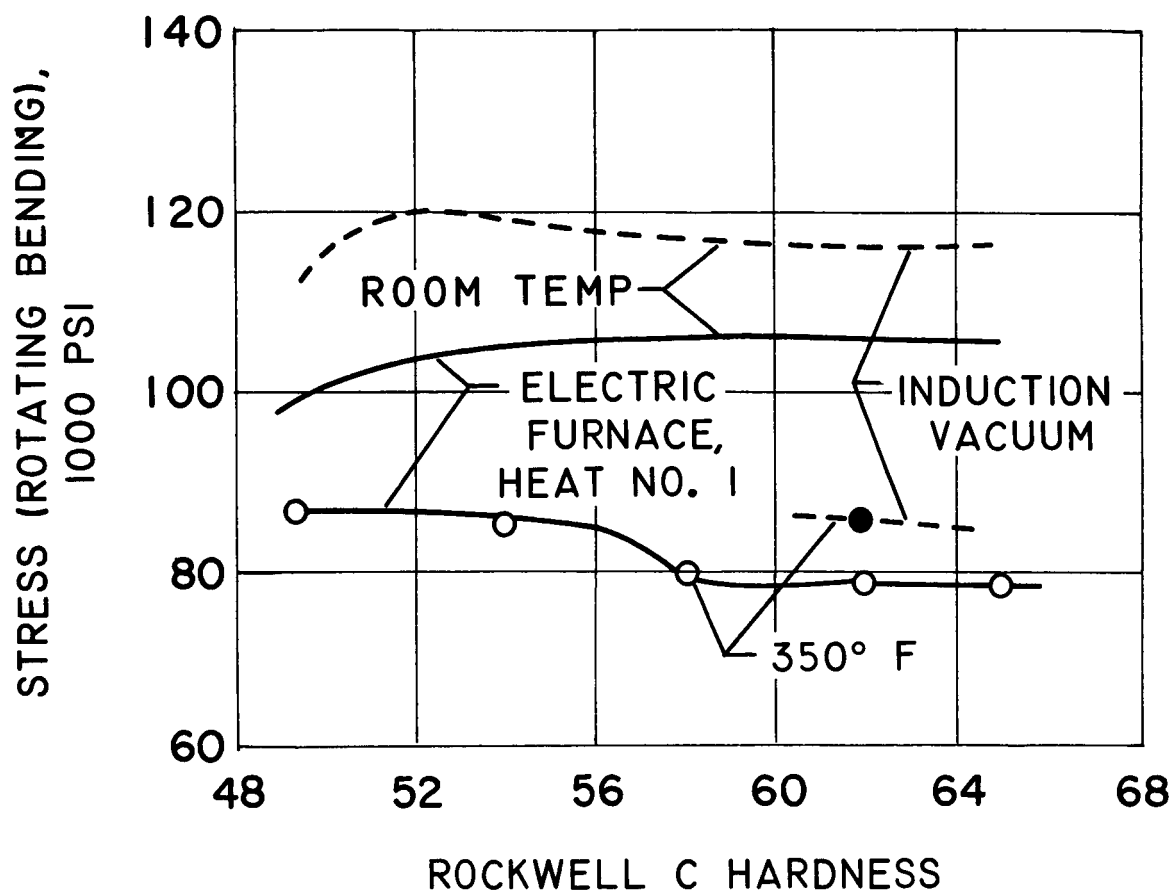


Fig. 16. - Comparison of room temperature and 350° F fatigue strengths at  $10^8$  cycles for an electric furnace and induction vacuum heat of SAE 52100.

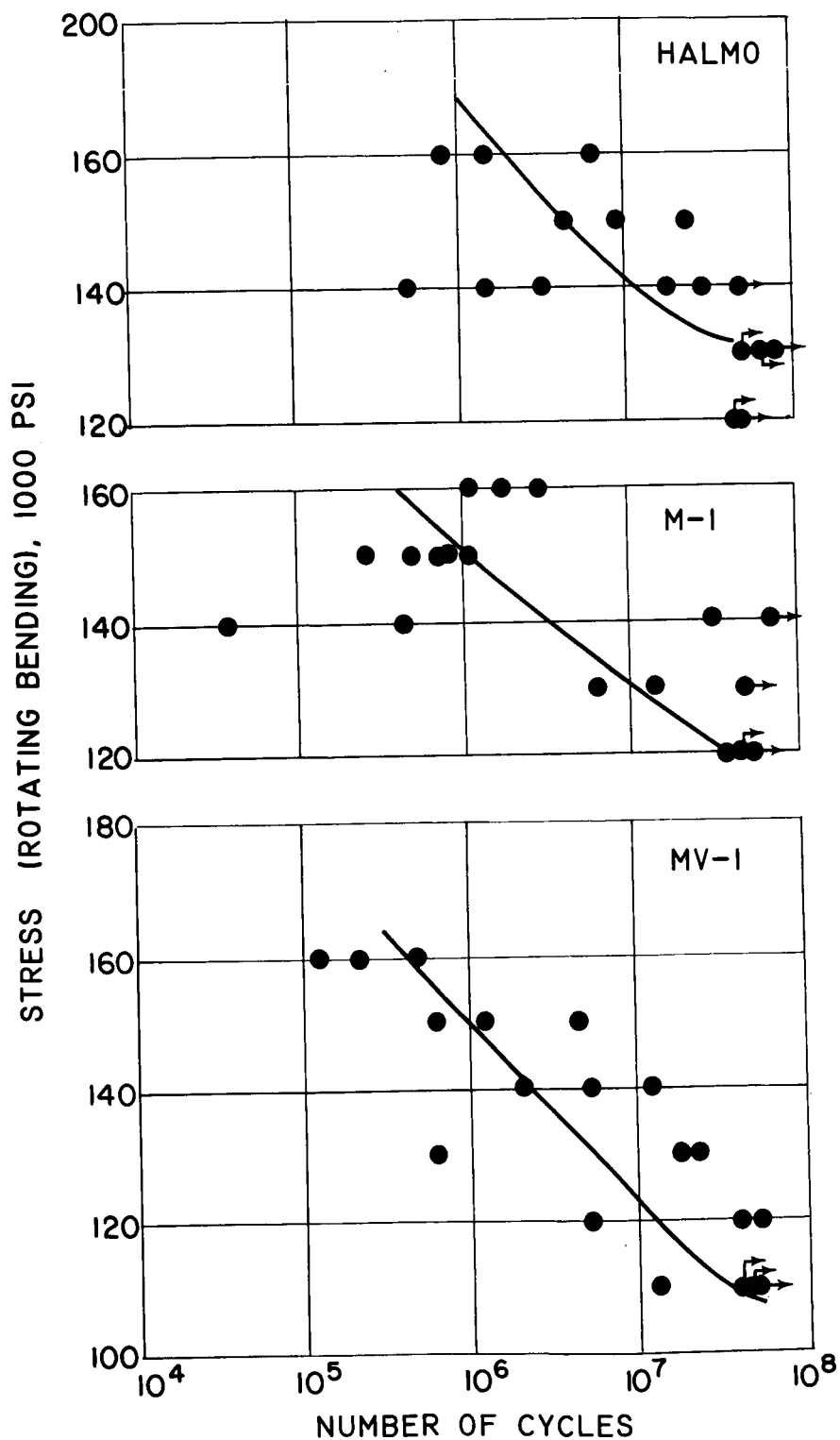


Fig. 17. - Room temperature S-N curves for the various tool steels commercially heat treated to 62 R<sub>c</sub>.

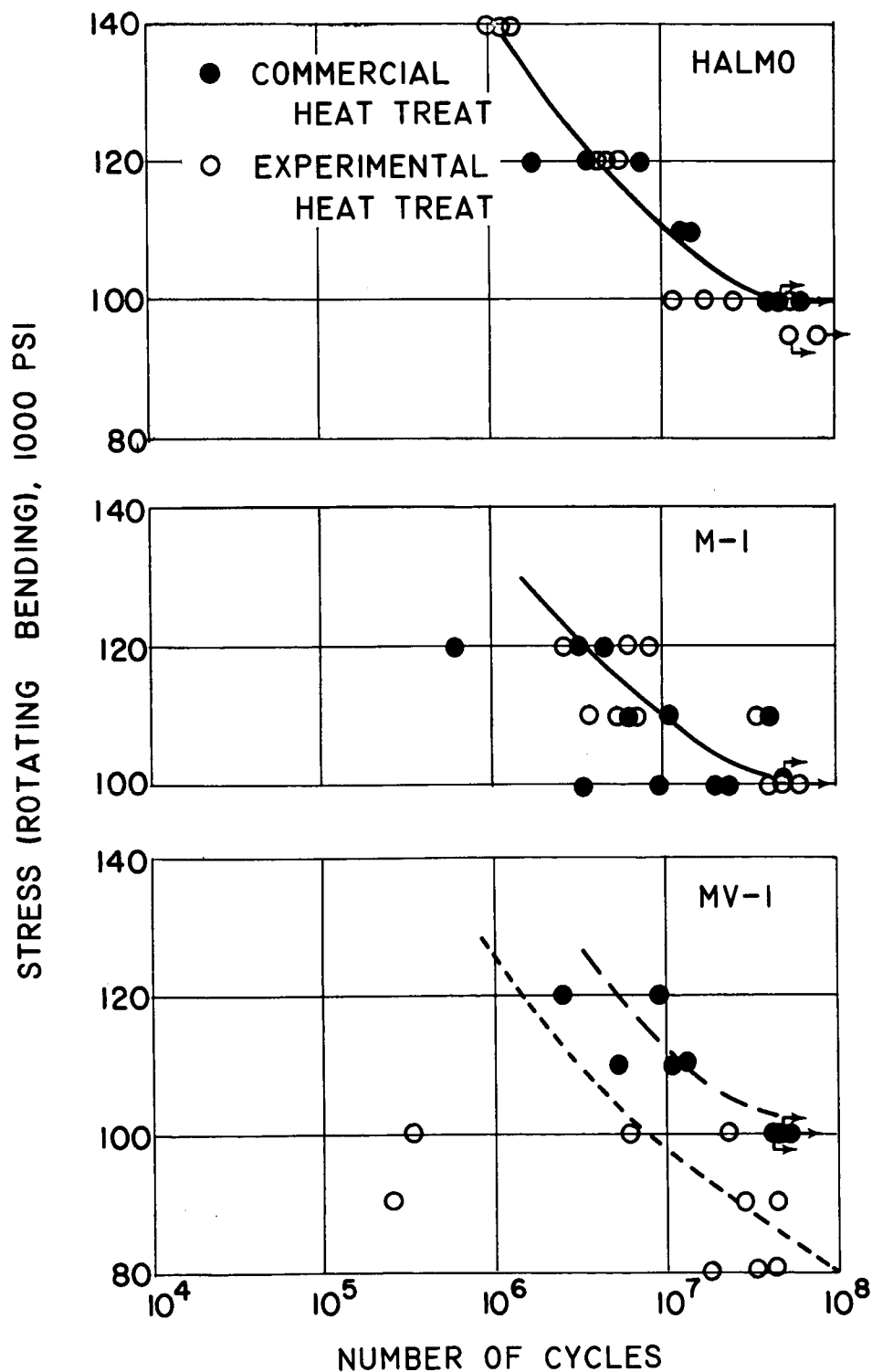


Fig. 18. - 500° F S-N curves for the various tool steels heat treated to 62 R<sub>c</sub> by two procedures.

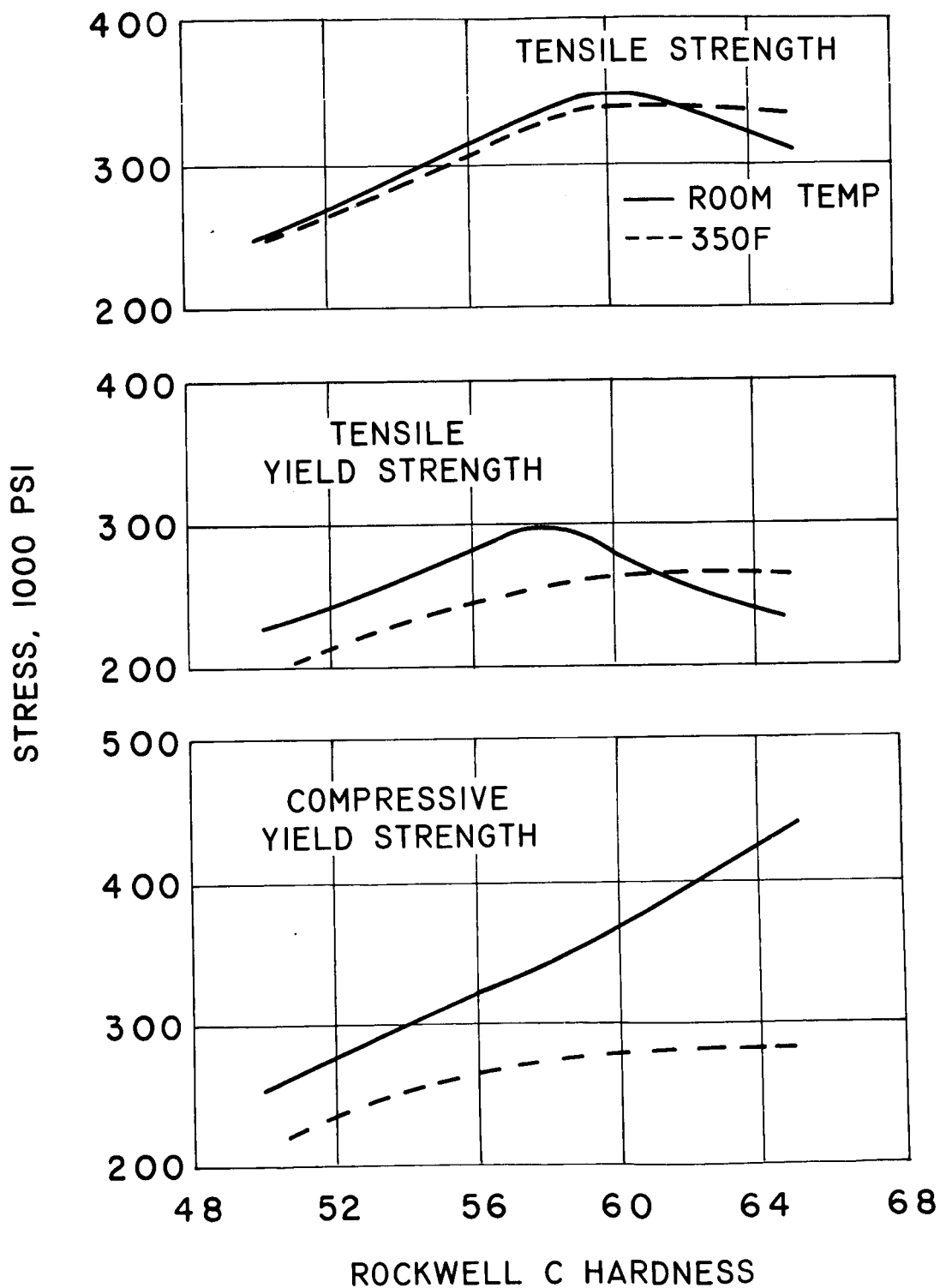


Fig. 19. - Comparison of room temperature and 350° F tension and compression characteristics for SAE 52100 heat no. 1.

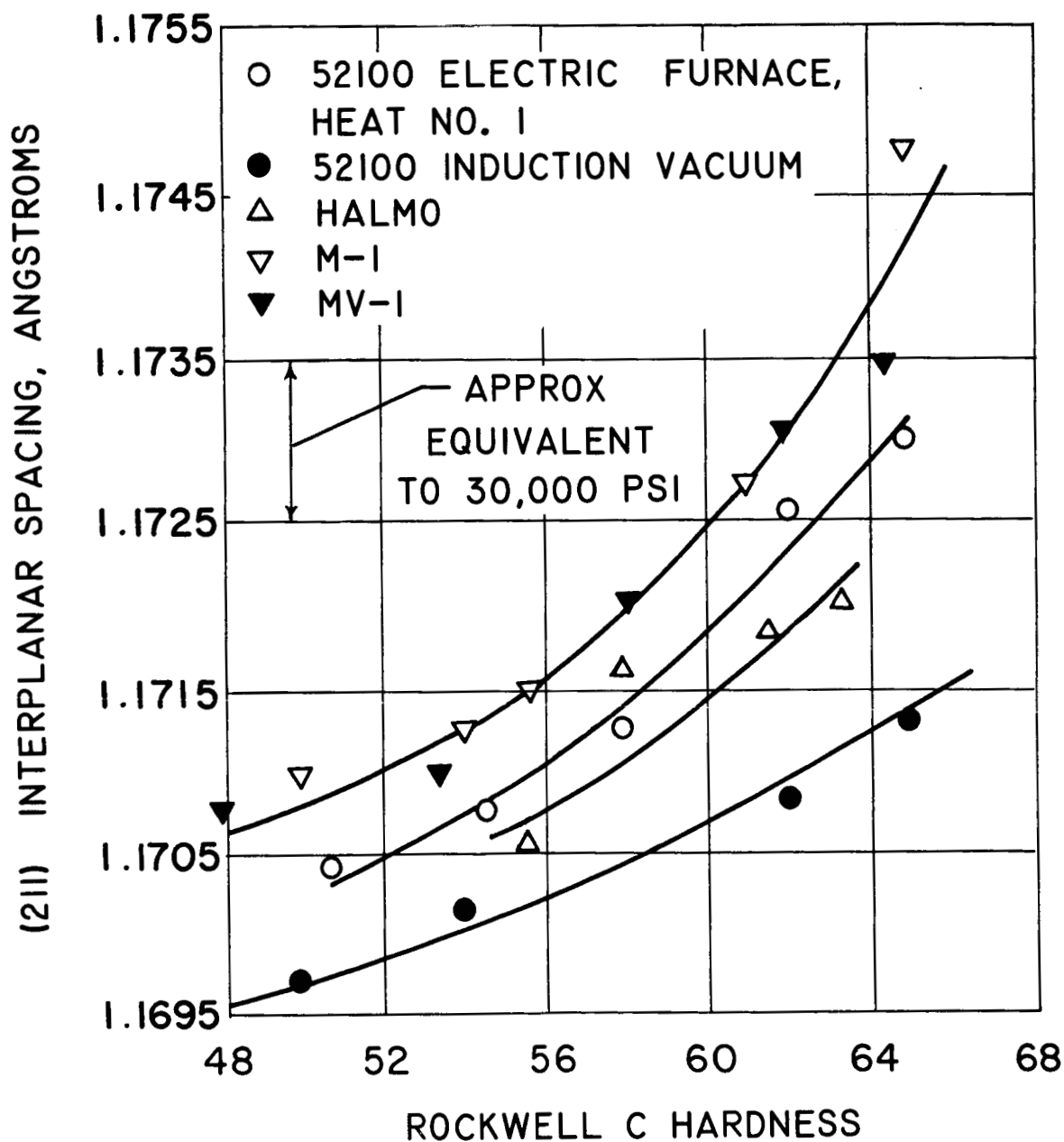


Fig. I-1. - Interplanar spacing of (211) planes as a function of hardness for various bearing steels.

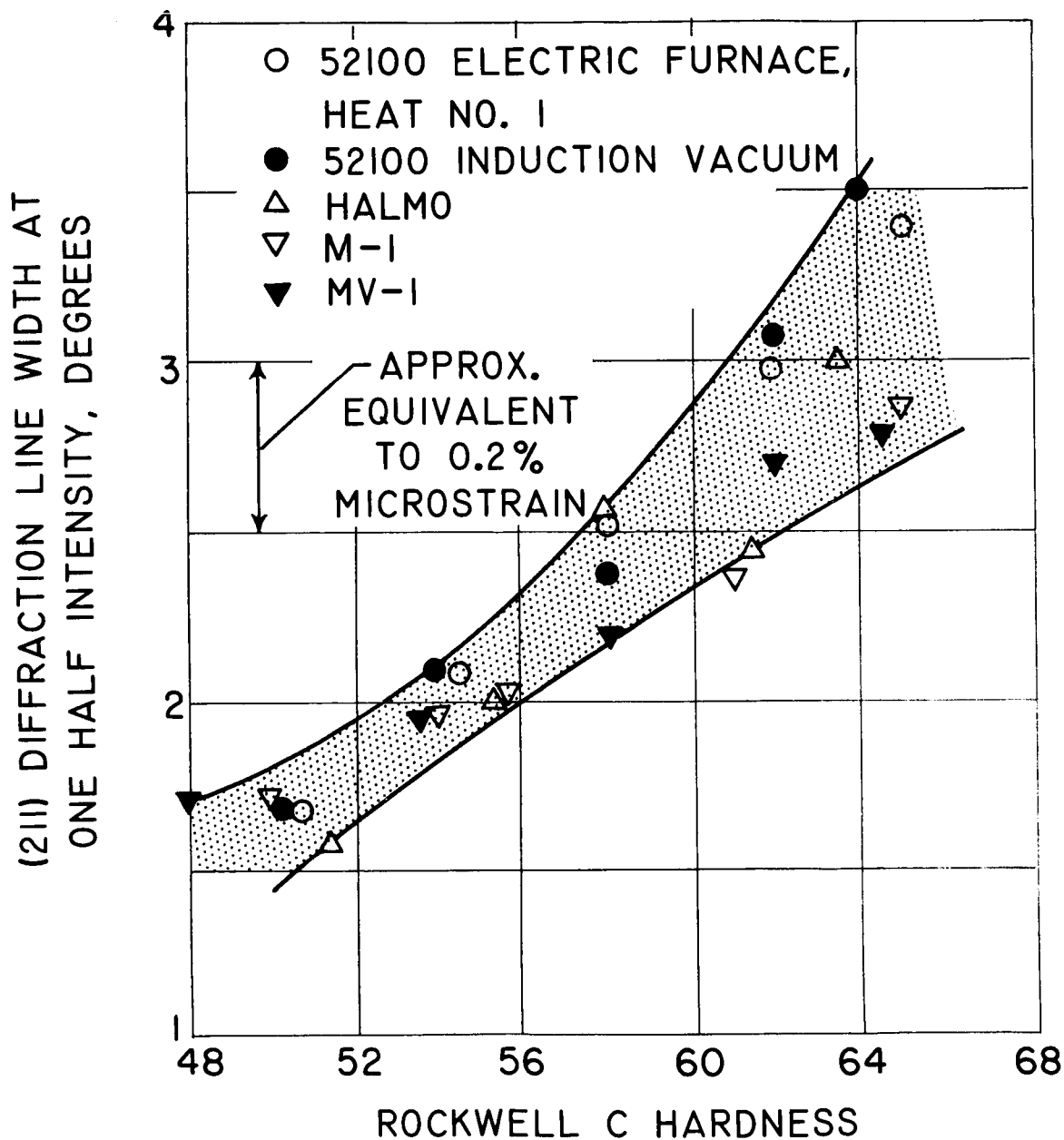


Fig. I-2. - Mean width of the (211) diffraction line as a function of hardness for various bearing steels.

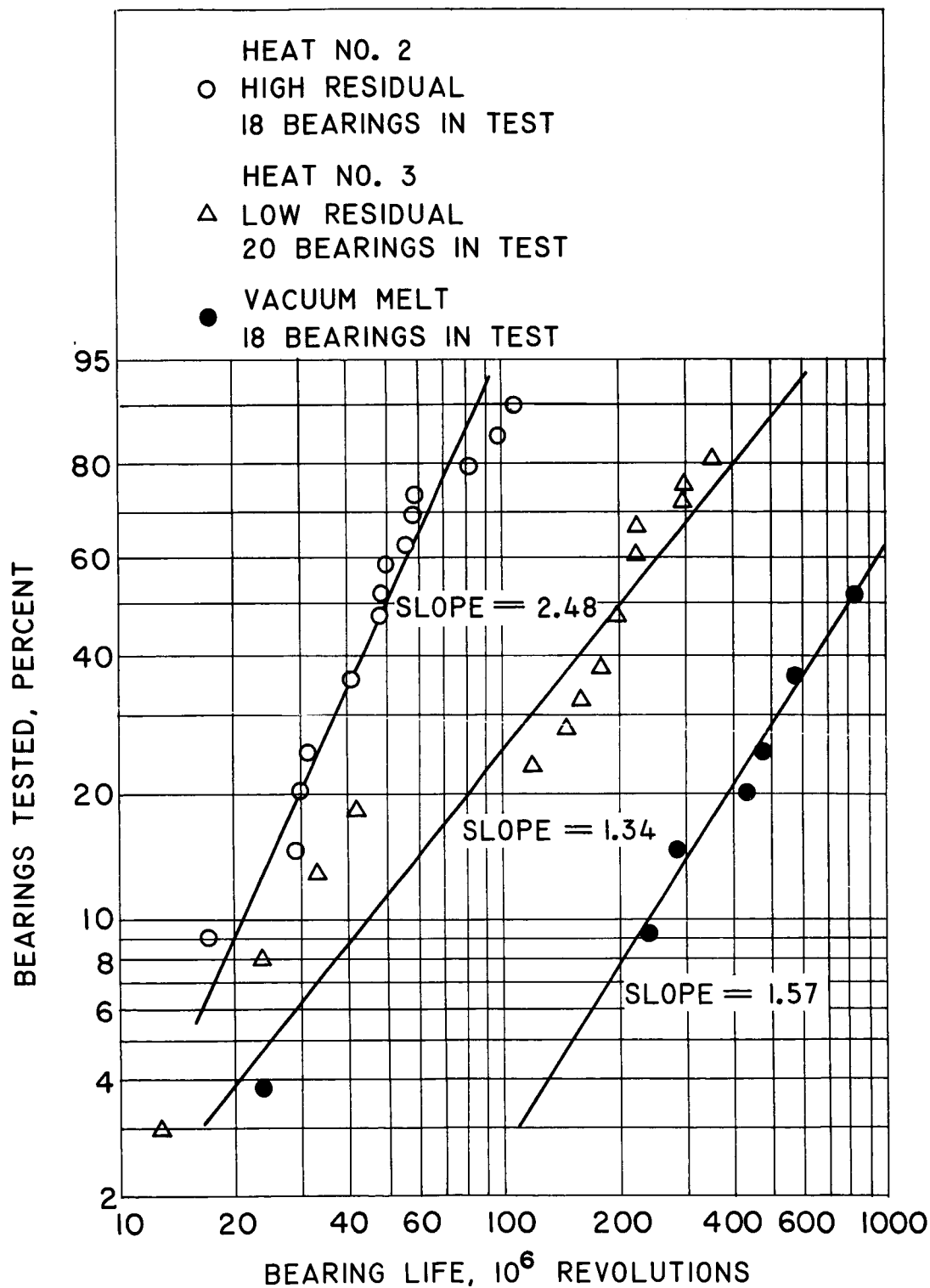


Fig. II-1. - Complete ball bearing data for various heats of SAE 52100 (M.R.C., Lundquist).